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The Effect of Preflood Nitrogen and Flood Establishment Timing on Rice Development, Nitrogen Uptake and Grain Yield

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The Effect of Preflood Nitrogen and Flood Establishment Timing on Rice Development, Nitrogen Uptake and Grain Yield

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ABSTRACT

Urea-N fertilizer is typically applied at the 5-leaf stage to rice (*Oryza sativa* L.) grown in a dry-seeded, delayed-flood production system. How long the preflood-N can be delayed without adverse effects on yield potential is poorly understood. The research objective was to determine the effects of preflood-N application and flood establishment timing on aboveground-N content, 50% heading, yield components, and grain yield. Trials were established on silt loam soils at the Pine Tree Research Station (PTRS) and Rice Research and Extension Center (RREC) during 2015 and 2016. Urea-N was applied at 0, 45, 90, 135, and 180 kg N ha^{-1} on five to seven different dates with applications beginning near the 3-leaf stage and ranging from 127-1035 growing degree units (GDU). The current optimal time to apply preflood-N is defined as 195-310 GDU. Aboveground-N content at each site-year, 50% heading for each cultivar and relative grain yield and yield components at each location were regressed across cumulative GDU at the time of N application allowing for linear and quadratic terms with coefficients depending on N rate. Aboveground-N content increased as fertilization and flooding were delayed. Spikelets $panicle^{-1}$, % filled spikelets, and effective tillers were affected by the fertilization delay at all locations. At the PTRS relative grain yield declined when fertilization and flooding occurred beyond 531 GDU suggesting that this is the point when the yield components could no longer compensate for one another. The delay in fertilization and flooding delayed 50% heading for all cultivars. Results from this study indicated that rice grain yield is affected when fertilization and flooding is delayed beyond 531 GDU, which is approximately 13 to 20 d beyond the current recommended time to apply preflood-N and 6 d beyond the current final recommended time to apply preflood-N average for the cultivars assessed in this study.

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DEDICATION

I would like to dedicate this thesis to my late grandfather, Ned Tomboli, who always inspired me and pushed me to further my education. I would like to also dedicate this to my advisor, Dr. Nathan Slaton, who without his continued enthusiasm, advice, and humor, this would not have been possible. I greatly appreciate everyone's support and help with making this thesis and my Master's career possible.

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Literature Review

Introduction

Efficient plant use of fertilizer nitrogen (N) depends on multiple factors including fertilizer properties, soil chemical and physical properties, crop characteristics, production system, and the field environment (e.g., temperature, humidity, rainfall, etc…). Fertilizer Nitrogen recovery efficiency (FNRE) by flood-irrigated rice (*Oryza sativa* L.) can be very efficient or inefficient depending upon the fertilizer-N source, crop growth stage, and field (e.g., atmosphere and soil) conditions present at the time of fertilizer application. De Datta et al. (1988) reported that the average FNRE by transplanted rice production systems in Asia was 20 to 40%. In contrast, Norman et al. (2003) and Wilson et al. (1989) indicated that rice grown in the mid-South USA using the direct-seed, delayed-flood production system can recover 60 to 75% of the applied preflood and midseason urea-N when fertilization follows very specific guidelines. Soil moisture and environmental conditions shortly before and after urea-N is applied preflood at the 4- to 5-leaf stage are key factors influencing FNRE by rice in the mid-South USA.

A large amount of research has been performed investigating preflood and midseason fertilizer-N management strategies for rice grown with the direct-seeded, delayed-flood production system. Numerous research studies have been published investigating fertilizer-N source (Norman el al., 2009), rate (Roberts et al., 2011), midseason-N timing (Wilson et al., 1998; 1989), soil moisture conditions (Norman et al., 1992; Dempsey et al., 2017), and the effect of the time between urea-N application and flooding (Norman et al., 2009). One aspect of fertilizer-N management that has not been adequately investigated is the timing of the preflood, urea-N application, which is important since the field conditions needed to obtain high FNRE as outlined in N fertilization recommendations are not always present at the 4- to 5-leaf stage (Norman et al., 2013b). For example, rainfall shortly before the 4- to 5-leaf growth stage may create wet soil conditions which is not desirable for the application of preflood urea-N in rice. Existing recommendations suggest delaying the preflood urea-N application until the soil is dry or until 3 wk before the predicted date that rice will reach the 1.25 cm (0.5 inch) internode elongation stage (Hardke et al., 2013). If preflood urea-N cannot be applied to a dry soil during the preflood-N application window, current guidelines suggest applying urea treated with a recommended urease-inhibitor, such as N-(n-butyl) thiophosphoric triamide (NBPT), to the moist soil to avoid loss of yield potential associated with N losses via ammonia volatilization (Norman et al., 2013b). The current DD10 (DD50) recommendation for the absolute deadline to apply preflood-N was established in the 1990s while using long-season cultivars and needs to be reevaluated (Slaton, personal communication). The duration of vegetative growth for modern varieties and hybrids has been reduced compared to the older longer season cultivars and the current recommendations are thought to be somewhat conservative. This literature review summarizes information regarding how rice is grown and fertilized in Arkansas and other mid-South, rice-producing states in the USA, highlights what is known about preflood urea-N fertilizer management for rice, and the effect of N fertilization timing on the yield of rice and other crops.

Rice Production Practices in the mid-South USA

Rice is an important commodity grown in the United States. In 2014, 1,189,371 ha (2,939,000 acres) of rice was planted within the United States (USDA-NASS, 2015b). The majority of rice is grown in only six states within the United States: Arkansas, California, Louisiana, Mississippi, Missouri, and Texas. Arkansas produces about one-half of the rice grown in United States and has been the top rice-producing state since 1973 (USDA-NASS, 2015a). In 2014, 598,934 ha (1,480,000 acres) of rice yielding an average of 8466 kg ha^{-1} (7,560 lb acre^{-1}) was harvested in Arkansas (USDA-NASS, 2015a**.** Rice is very important to the Arkansas economy and is planted on more land area than all other row crops except soybean (*Glycine max* (L.) Merr.), which is grown on 1.3 million ha (3.23 million acres; USDA-NASS, 2015d) and is the primary crop grown in rotation with rice. A rice-soybean rotation is used on approximately 72% of the Arkansas rice hectares (Hardke, 2014).

Pureline cultivars and hybrids are both grown throughout the mid-South. The majority of the rice grown in Arkansas is long-grain, however, medium-grain rice accounts for about 14% of the Arkansas rice hectares (Hardke, 2014). Hybrid rice has been grown in Arkansas since the early 2000's and now occupies about 39% total Arkansas rice hectarage.

There are two main types of management options for lowland rice, direct-seeded and transplanted rice. Transplanting is the most popular rice planting method in Asia (De Datta, 1981), but is not practiced in commercial production in the USA. Transplanting rice involves first growing the seedlings in a nursery and once the seedlings reach the 5-leaf stage, placing them into a flooded soil. The transplanted rice establishment method is labor intensive and parts of Asia are transitioning to direct-seeding methods (Schnier et al., 1990).

Direct seeding is the predominant rice management method practiced in the mid-South USA. The direct-seeding system involves direct application of seed to a dry (dry seeding) or flooded (water seeding) field. For the dry seeding method, seed is planted via drill or broadcast using an airplane or ground application equipment. In Arkansas, 96% of the rice area is planted using the dry-seeded planting method (Hardke, 2014). With the broadcast method, pre-germinated seed is dispersed into the floodwater via airplane (water seeded) or dry seed is spread onto dry soil and covered using shallow tillage. Drill-seeded rice accounts for 85% of the total rice hectares in Arkansas (Hardke, 2014). Rice seed is generally drilled 0.8-2.5 cm deep with 15-25 cm wide row spacing (Street and Bollich, 2003).

Conventional tillage and conservation tillage (no-till) practices are used in rice production systems. Conventional tillage systems involve incorporating crop residue into the soil by mechanical cultivation which is often performed in the fall months; additional tillage in the spring is also required to prepare a suitable seedbed and destroy weedy vegetation prior to planting (Bollich, 1991). Conservation tillage systems often allow crop residue incorporation into the soil by cultivation and leveling the seedbed during the fall. Winter vegetation is killed using a burndown herbicide application 2 to 4 wk prior to seeding (Harrell et al., 2011). Prior to the year 2000, rice in the United States was most commonly grown using conventional tillage practices, however, conservation tillage practices have increased in popularity in an effort to conserve water, nutrients, and soil resources (Bollich, 2000).

A computer program known as the DD10 (DD50) is currently available free to Arkansas rice producers to predict critical dates and guide rice management practices (Hardke et al., 2013). The DD10 program has been used by Arkansas rice producers for the past 40 yr. Several rice-producing states have a similar program but none provide the diversity of information as does the Arkansas program. Twenty-six management decisions based on rice growth stages assist growers in determining when to apply herbicide, when to scout and spray for insects and diseases, how to manage water, and the optimum time to apply fertilizer-N. The field location, emergence date, field size (e.g., hectares), and cultivar are required to enroll a field in the DD10 program. The location is taken into consideration when running the program due to latitude climatic differences. For example, locations in northern Arkansas usually take 2 d longer for rice to reach specific growth stages than locations in southern Arkansas (Hardke, personal communication). The program is calculated based on 30-yr mean temperatures from specific weather stations and prediction accuracy is increased with each day that passes from the use of current-year weather data. The DD10 program uses a growing degree day equation to calculate the number of daily heat units accumulated {DD10= [(daily maximum temperature (^{o}C) + daily minimum temperature (^{o}C) / 2] – 10} ({DD50 = [(daily maximum temperature (^{o}F) + daily minimum temperature (^{o}F)) / 2] – 50}). Maximum and minimum temperatures, 34^{o}C (94^{o}F) and 21^{o}C (70^{o}F), respectively, are used to regulate unit accumulation due to threshold temperatures for rice development. A maximum of 17.8 (32) growing degree day units (GDU) can be accumulated in 1 d. The program requires annual research to determine the maturation rate of new rice cultivars grown using the direct-seeded, delayed-flood production system. Deviations from the management practices (e.g., flood time, use of high or low N rates, crop injury, etc...) that define this system as practiced in Arkansas may cause some error in the program's predictions.

In Arkansas, rice is usually planted from late March through May and is harvested in late August or September (Hardke, 2014). A good environment for rice stand establishment begins when the soil is 16^{o}C (60^{o}F) at a soil depth of 10 cm (4 inches). The optimum seeding rate is influenced by several factors: seeding method, soil texture, seedbed preparation, and seeding date. The standard seeding rate is based on drill seeding rice into a loamy soil with a good seedbed at a rate to plant 323 seed m^{-2} for pureline cultivars (30 seed ft^{-2}). Seeding rates are adjusted for a number of factors including early or late seeding (10 and 20% increase, respectively), water seeding (30% increase), broadcast seeding (20% increase), clayey soils (20% increase), and seedbed condition (10 and 20% increase for fair and poor conditions, respectively)

(Runsick and Wilson, 2009). The same adjustments are used for hybrids but the recommended base seeding rate is 129 seed m^{-2} (12 seed ft^{-2}).

Rice Growth Stages

Rice has three growth phases seedling, vegetative, and reproductive that collectively encompass 110-150 d between emergence and maturity (Moldenhauer et al., 2013). The following information pertaining to the accumulation of DD10 units was obtained from Moldenhauer et al. (2013), while the rice development stages were obtained from Counce et al. (2000). The seedling growth phase includes four stages prior to spike emergence (S0-S3). The S0 stage occurs when the seed has not yet imbibed water, while S3 denotes the emergence of the prophyll (first leaf) and signifies "emergence" for the DD10 program. Good seed-to-soil contact is required for optimal germination at a depth of 1.3 to 3.8 cm (0.5 – 1.5 inches). Optimal seed germination occurs when the seed is exposed to moisture, oxygen, and a temperature greater than 10^{o}C (50^{o}F).

The vegetative growth phase encompasses seedling emergence through tillering and consists of two primary stages: pretillering (V1-V4) and tillering (V5-V20). The vegetative growth phase can range anywhere from 24-42 d and is dependent on several factors (e.g., temperature, moisture, cultivar, soil texture, competition, and fertilization). Seedling emergence typically occurs 5-28 d after planting and is followed by the pretillering vegetative stage that can last 15-25 d. During the pretillering stage, the plant adds, on average, one leaf wk^{-1}. The tillering stage begins once the fifth leaf has emerged and lasts until the reproductive phase begins. During tillering, new leaves emerge every 3-5 d, and tillering can last 24-42 d. A 'vegetative lag' stage may be present in some cultivars during the transition from the vegetative to reproductive phase.

The reproductive phase consists of nine stages: panicle initiation (PI, R0), internode elongation (IE, R0), panicle differentiation (PD, R1), flag leaf collar formation (booting, R2), panicle exertion (heading R3), anthesis (flowering, R4), grain length and width expansion (R5), grain depth expansion (milk stage and soft dough stage, R6), grain dry down (hard dough stage, R7), single grain maturity (R8) and complete panicle maturity (R9). Panicle initiation is also referred to as ‘green ring’, which is a sign that internodes will begin to elongate. The onset of internode elongation is also referred to as ‘jointing’, and occurs when the nodes are visibly separated and begin to move up the stem. The R1 growth stage is described as the stage when a 1.25 cm (0.5 inch) internode gap is present between the two uppermost nodes. The 1.25 cm internode gap typically occurs when 618 to 944 DD10 (1100-1680 DD50) units have accumulated with the number of days being dependent upon environmental conditions, latitude, cultivar, and planting date. The transition from R1 to R2 is 20-30 d, with the R2 (booting) stage beginning when the flag leaf develops a collar. Booting stage occurs when the flag leaf begins to swell and late boot occurs 6 d prior to heading and is identifiable once the flag leaf emerges. Heading can take up to 14 d and is identifiable when the panicle emerges completely. A field reaches 50% heading when 50% of the panicles are at least partially exerted from the boot. Modern cultivars typically reach 50% heading when 1011 to 1404 DD10 (1800-2500 DD50) units have accumulated and is mainly dependent upon the cultivar. Anthesis, the R4 stage, occurs 2 d after heading, lasts up to 3 h, and occurs when the floret opens to allow pollination.

The R5-R8 stages can be summarized as the ripening and maturity portion of the reproductive phase. The R5 stage represents the period when the caryopsis expands inside the hulls before grain fill begins. Ripening consists of three stages (milk stage, R6; soft dough stage, R7; hard dough stage, R8). Milk stage occurs when the kernel is filled with milk and soft dough occurs when the milk starts to solidify. The hard dough stage (R7) occurs 7 d following R6, while R8 occurs 2-5 d following R7. The maturity stages comprise the stages of grain moisture loss (R8) and rice maturity (R9). The R8 stage involves moisture loss from the grain until the grain is harvestable. Rice is considered mature (R9) when the grain moisture content is <220 g H_2O kg^{-1} and is ready for harvest. The period between 50% heading and grain maturity is dependent of several factors but is generally estimated to require 35 to 45 d (Moldenhauer et al., 2013). The DD10 program does not use heat units to predict growth stages beyond 50% heading, but uses grain type (e.g., short, medium, and long grain) to estimate maturation date. Once the heads have emerged, kernel size, the size of the panicle, number of spikelets $panicle^{-1}$, and environmental conditions determine the duration until maturity.

Rice Water Management

Water management is perhaps the most critical management practice since it influences all other aspects of rice production including nutrient management, crop susceptibility to pests (diseases, insects, and weeds) and their control. The delayed-flood management method is used on 96% of the Arkansas rice hectares with only 4% of rice produced in a water-seeded system (Hardke, 2014). Furrow-irrigation is used on only 0.4% of the rice grown in Arkansas. A delayed-flood system is where the rice is grown like an upland crop [e.g., wheat (*Triticum aestivum* L.)] until the 4- to 5-leaf stage at which time the rice is flooded and the flood is generally maintained for the remainder of the growing period until floodwater is drained to prepare for harvest (Norman et al., 2009). On average, rice requires 7,615 m^3 irrigation-water ha^{-1} yr^{-1} (30 acre-inches irrigation-water) (Scott et al., 1998). The direct-seeded, delayed-flood management practice can result in high FNRE if used appropriately (Griggs et al., 2007). However, the time required for commercial production fields to establish a permanent flood can range from 2 d to a few weeks, depending upon field size and pumping capacity. How efficiently (e.g., quickly) a producer can establish a flood after urea-N is applied directly influences how much urea-N may be lost via NH_3 volatilization and affect overall FNRE.

Rice Nitrogen Management

Nitrogen is the nutrient most commonly limiting cereal crop production worldwide and is the fertilizer nutrient applied in the greatest amounts. Efficiency of fertilizer-N uptake by plants is governed by soil properties, climatic factors, agronomic practices, crop species, and the management of fertilizers. Despite the large amount of research that has been conducted on fertilizer-N management for crop production, continual improvements in cultivars, changes in production practices, development of new fertilizers, and the interactions among these factors coupled with the overall importance of N nutrition for maximizing crop yield warrant additional N management research.

Rice is a non-legume crop meaning it does not have the ability to fix atmospheric N_2 and requires fertilizer-N to reach its yield potential on most soils. Total fertilizer costs represent the single greatest expense for rice production accounting for \$350 ha^{-1} (\$136 A^{-1}, USDA-NASS, 2015c) and 21% of a typical production budget (Flanders et al., 2015). Nitrogen alone represents 48% of the fertilizer costs (\$169 ha^{-1} or \$66 A^{-1}), which is about 10% of the entire input cost of a rice production budget. Because fertilizer-N represents a substantial percentage of most crop production budgets and is associated with environmental quality issues, proper management is crucial for the economic success of rice growers.

Field-specific, fertilizer-N rates can be determined for rice grown in the delayed-flood production system using soil samples collected from the top 45 cm (18 inches) in loamy soils and the top 30 cm (12 inches) in clayey soils (Roberts et al., 2011; Norman et al., 2013a; Fulford, 2014; Greub, 2014). The N-STaR soil-N test is used to determine the amount of plant-available N in the soil profile which includes determination of alkaline-hydrolyzable N (e.g., NH_4-N, amino acid-N, and amino sugar-N) using direct-steam distillation (Roberts et al., 2011). Alternatively, growers can use the standard fertilizer-N recommendation that is based on the crop grown before rice, cultivar/hybrid, and soil texture (Norman et al., 2013a; Roberts and Hardke, 2016).

There are two fertilizer-N application options for rice grown in the delayed-flood system, the optimum single preflood and the standard 2-way split application methods. The standard fertilizer-N rate needed to achieve optimum yield is cultivar dependent, but usually ranges from 134 to 168 kg N ha^{-1} (Roberts et al., 2013a, 2013b). Preflood urea-N should be applied onto a dry soil and accounts for 60 to 100% of the total fertilizer-N required (Norman et al., 2013b). The preflood-N rates typically range from 100 to 150 kg N ha^{-1} for rice grown on loamy soils using the standard recommendation based on the fertilization method, soil texture and cultivar requirement. The taller rice cultivars that are prone to lodging typically require less fertilizer-N. The single optimum preflood method is suggested for fields that can be flooded in a timely fashion and urea-N can be incorporated into the soil within 5 d. Ammonia volatilization can start within 2 d of urea-N application and 30 to 90% of urea-N applied can be lost in 3 to 7 d (He et al., 1999). The 2-way split method involves applying 70% of the fertilizer-N preflood on a dry soil and applying the remaining 30% between panicle initiation and differentiation. According to Wilson et al. (1989), rice grown in the delayed-flood, production system requires about 3 wk to take up the preflood applied urea-N, with FNRE values of 75% when urea is applied to a dry soil and flooded rapidly. The early preflood-N application sets the yield potential for rice and if managed correctly, there is no need for an N application at midseason (Bollich et al., 1994;

Norman et al., 2001). For the 2-way split application method, the total N requirement of the cultivar is divided between the 5-leaf stage and midseason with 52 kg N ha^{-1} applied in a single dose near the 1.25 cm IE stage and the balance of the fertilizer-N rate applied preflood (Norman et al., 2013b). The 2-way split method is recommended when using hybrid rice cultivars. Hybrids can maximize yield with a single optimum preflood-N application, however, they are prone to lodging and a late boot N application of 34 kg N ha^{-1} is recommended to minimize lodging (Norman et al., 2013b, 2006).

Rice grown on clayey soils usually requires 34 to 67 kg N ha^{-1} more N to maximize yield than rice grown on loamy soil (Roberts et al., 2013b). Although clayey soils usually contain more total-N the greater fertilizer-N requirement is thought to be due to clay fixation and the slower diffusion of NH_4-N because of the small pore size and greater pore space (tortuosity) associated with the larger clay content (Trostle et al., 1998). The midseason urea-N is applied into the floodwater and is taken up by the rice plant within 3 d after application with a FNRE of about 58% (Wilson et al., 1989).

Research involving rice response to fertilizer-N has examined how grain yield and FNRE are affected by inorganic-N form (Moore et al., 1981; Westcott et al., 1986; Norman et al., 1988; Wilson et al., 1989; Norman et al., 2009), organic-N (Westcott and Mikkelsen, 1987; Cabrera et al., 2005; Brye et al., 2006; Golden et al., 2006; Reiter et al., 2014), fertilizer-N application timing (Westcott et al., 1986; Wilson et al., 1989; Norman et al., 1992; Norman et al., 2009), and urease and nitrification inhibitor amendments (Clay et al., 1990; Qui-xiang et al., 1994; Rao and Popham, 1999; Pasada et al., 2001; Carrasco et al., 2004; Norman et al., 2009; Fitts et al., 2014; Rogers et al., 2015; Dempsey et al., 2017), but we could find not information stating why preflood-N is usually applied at the 4- to 5-leaf stage. Proper management of the preflood-N is extremely important since the early-season N availability sets rice yield potential (Wilson et al., 1989). The 4-to 5-leaf stage coincides with the accumulation of 195 to 310 DD10 units (350 to 550 DD50) and is the current recommended optimum time to apply preflood-N and establish the permanent flood (Norman et al., 2013b). The current recommendation for the absolute final time to apply preflood fertilizer is provided in the current DD10 program; this recommendation occurs 287 DD10 units (16 d, 510 DD50 units) before 1.25 cm IE which corresponds to about 10 d prior to the beginning IE (green ring) prediction. Thus, the final recommended time to apply preflood fertilizer-N depends on the duration of each cultivar's vegetative growth stage. The current recommendation for the preflood-N cut-off was established from conservative interpretation of research performed by Norman et al. (1992). Determining the absolute latest time that preflood fertilizer-N can be applied to rice is critical preflood-N management information that will be discussed in more detail later in the literature review.

Nitrogen Dynamics

Soil- and fertilizer-N can be lost via ammonia (NH_3) volatilization, denitrification, immobilization, leaching, erosion, and runoff. Each of these N loss pathways can be reduced by applying fertilizer-N at a time that coincides with active nutrient uptake by the root system (Alcoz et al., 1993; Cassman et al., 1998; Scharf, 2015). The two primary N loss pathways in rice are ammonia volatilization from urea and denitrification. For flood-irrigated rice, the fertilizer source (Bufogle et al., 1998; Golden et al., 2009; Norman et al., 2009), N transformations of soil- and fertilizer-N prior to flooding (Beyrouty et al., 1988; Griggs et al., 2007), and soil conditions at the time of fertilizer-N application (Norman et al., 1992; Griggs et al., 2007; Golden et al., 2009; Dempsey, 2015) all play important roles in determining the FNRE of rice.

Ammonia volatilization is a key N loss pathway in rice production worldwide and is believed to account for 84 to 88% of the total N lost in rice production systems (De Datta et al., 1991). Ammonium-producing fertilizer sources, such as granulated urea [$(NH_2)_2CO$], are susceptible to NH_3 volatilization when left on the soil surface and not incorporated. Environmental factors including, but not limited to, temperature, timing of N application, soil pH, wind, and soil moisture influence NH_3 volatilization loss potential (Ernst and Massey, 1960). The potential for NH_3 volatilization loss increases as soil pH, temperature and moisture increase. For example, Ernst and Massey (1960) reported 50% of the added urea-N was lost due to NH_3 volatilization at a soil pH of 7.5 compared to only 10% loss at a soil pH of 5.5. Ammonia volatilization losses increase with factors that increase evaporation, such as high air and soil temperatures, high soil moisture conditions, and wind speed (Ernst and Massey, 1960; Keeney and Bremner, 1967; Schmidt, 1982; Kyveryga et al., 2004). Three general rules of urea-N management include apply the urea to a dry soil surface, incorporate the urea within 2 d with moisture (rainfall or irrigation), and amend urea with an effective urease inhibitor (Griggs et al., 2007; Norman et al., 2009, 2013b; Dempsey et al., 2017). Norman et al. (2009) showed NH_3 volatilization of urea-N increased from 17 to 24% of the added urea-N when applied 5 and 10 d, respectively, prior to the establishment of a permanent flood. The use of the urease inhibitor known as NBPT is recommended to reduce the amount of NH_3 volatilization that occurs from urea-containing fertilizers. The NBPT inhibits urea hydrolysis for several days, which allows dilution of urea concentration (e.g., around the urea prill) in soil via diffusion, and thereby aids in reducing NH_3 volatilization (Clay et al., 1990; Henderickson, 1992).

Nitrification is the conversion of ammonium-N (NH_4) to nitrate-N (NO_3) by soil microbes. Nitrification is an aerobic process and soil temperature and pH play important roles in determining how rapid the nitrification proceeds. The nitrification of NH_4-N derived from soil and fertilizer-N is optimized by warm and moist soil conditions and the nitrification rate increases as pH increases (Focht and Verstraete, 1977; Belser, 1979; Schmidt, 1982). Soils used for rice production in the mid-South, USA, tend to have a rapid rate of nitrification and the one-half life of urea-N added under warm, moist conditions in the laboratory ranges from 4 to 15 d (Fitts et al., 2014). Nitrification inhibitors can be applied to N fertilizer to delay the conversion of NH_4-N to NO_3-N (Sutton, 2005). Inhibitors that slow the nitrification rate of fertilizer-N, and subsequently denitrification, can optimize FNRE by crops resulting in the potential for increased crop yields and decreased production costs, but have not shown much potential as a urea-N management aid for rice in the mid-South USA (Fitts et al., 2014; Dempsey, 2015). Nitrate is a highly mobile N form and is an undesirable inorganic-N form for rice because it is prone to leaching and denitrification (Whitehead, 1995).

Denitrification, the microbial conversion of nitrite-N (NO_2) and nitrate-N (NO_3) forms to gaseous N forms (e.g., N_2 and N_2O) occurs when oxygen availability in the soil is limited (Reddy et al., 1978; Patrick, 1982). Flooding the soil to grow rice creates anaerobic conditions, which inhibits nitrification and creates an environment conducive for denitrification. Season-total N loss via denitrification is maximized when a field undergoes a number of aerobic followed by anaerobic cycles (Patrick and Wyatt, 1964; Patrick, 1982). The N_2O gasses are powerful greenhouse gasses that reduce overall air quality. The rate of denitrification increases rapidly as temperatures increase from 2 to 25^{o}C while the optimal temperature for denitrification is 60^{o}C (Bremner and Shaw, 1957; Keeney and Bremmer, 1967). The rate of denitrification increases as soil pH increases beyond 5.5 up to 8.6 (Bremner and Shaw, 1957; Schmidt, 1982). Denitrification mainly occurs when the soil is saturated, flooded or severely compacted, but can occur when soil is not completely flooded, since oxygen availability may be limited in microsites in the soil (e.g., near decomposing organic matter and fertilizer-N due to high microbe activity; Liu et al., 2007; Halvorson and Del Grosso, 2013; Maharjan and Venterea, 2013; Halvorson et al., 2014).

Nitrogen Deficiency

Nitrogen deficiency is the most frequently observed nutrient deficiency symptom in rice production (Dobermann and Fairhurst, 2000). Nitrogen deficiency may be noticeable during the vegetative and reproductive growth stages due to fertilizer-N loss, insufficient soil-N content, and insufficient fertilizer-N rate. Visible N deficiency symptoms during the vegetative growth stage include a reduction in tiller number and leaf chlorosis (leaf yellowing). Leaf chlorosis is the premature aging of leaves due to reduced photosynthesis within the rice plant (Crafts-Brandner et al., 1996, 1998). Photosynthesis decreases as the severity of N deficiency increases (Huang et al., 2004). Nitrogen deficiency results in lower chlorophyll concentrations and a reduction in chloroplast numbers in leaves (Chen et al., 2003). Nitrogen deficiency during the reproductive stage (R0-R4) could reduce the number of spikelet's panicle^{-1} and increase the number of unfilled spikelet's (Fageria and Baligar, 1999).

Effect of Nitrogen Application Timing on Crop Yield

Nitrogen is the nutrient that influences cereal crop yields to the greatest extent on most soils and must be applied as fertilizer to maximize yield. Cereal crops appear to have an absolute growth stage by which time fertilizer-N must be applied before irreversible yield loss will occur on N deficient soils. The flood irrigation used for rice production makes proper preflood-N management important for obtaining high FNRE and producing maximal yield. The dry soil condition desired for preflood-N management is critical for high FNRE and is not always available when rice begins to tiller (Norman et al., 2013). During years when frequent and untimely rainfall maintains moist field conditions, rice growers want to know is it more beneficial to wait for the soil to dry and possibly compromise grain yield from late N fertilization or apply urea-N to a moist soil, which increases N loss and will likely require additional N to be applied to maintain yield. Fertilizer-N application time studies have been conducted on a number of non-legume crops including rice, wheat, corn (*Zea mays* L.), and cotton (*Gossypium hirsutum* L.), which can be used to guide to answer the question of how late can fertilizer-N be applied before yield reduction occurs?

The literature contains limited information on how fertilizer-N application time influences rice grain yield. Fageria and Baligar (1999) noted that N applied during the reproductive stages beyond R2 (booting) in lowland rice does not increase yield, because yield potential is established by the availability and uptake of adequate N during vegetative growth. Wilson et al. (1989) also noted that if early-season N availability was insufficient, the efficiency of N uptake and yield response to midseason fertilizer-N was limited. Fertilizer-N applied beyond the R2 growth stage can be absorbed by the plant, however, N taken up late in the growing season does not benefit yield (Wilson et al., 1989). The results reported by Fageria and Baligar (1999) and Wilson et al. (1989; 1998) both indicate that early-season N deficiency limits rice yield potential and delaying fertilizer-N application beyond some critical stage limits yield potential.

Norman et al. (1992) reported that delaying the preflood-N application and flood for 21 d beyond the 5-leaf stage had no significant effect on grain yield, but noted that heading was delayed as the preflood-N application and permanent flood establishment were delayed. Although total-N (soil + fertilizer) uptake was unaffected by fertilizer-N application time, fertilizer-N uptake and harvest index both increased as the preflood-N and flood timing were delayed. Soil-N uptake was slightly less or remained unchanged by fertilizer-N application time. A preliminary trial conducted by Slaton et al. (2015) also showed that the yield of rice planted in late April was maximized by urea-N applied from 4 June through 27 June. Slaton et al. (2015) reported that the yield of rice receiving no fertilizer-N actually increased, as the urea-N application and flood establishment were delayed suggesting greater uptake of soil-N from delaying the flood. The limited information available for rice indicates that the optimal window to apply preflood-N or the permanent flood has not been thoroughly evaluated and warrants additional research with rice and examination of the yield response of other crops to fertilizer-N and flood timing. Due to the limited information available for rice, the response of other crops that require fertilizer-N might be of value for understanding how plant development and yield potential interact with N nutrition.

Rice grain yield and yield components are maximized by having an adequate amount of N available at the proper time. Moldenhauer and Gibbons (2003) explained that rice yield components were established at different growth stages including panicle number area^{-1} is established during vegetative development (stand and tillering), spikelet number panicle^{-1} is determined at PD, the percentage of filled or unfilled spikelets is determined between R1 and R4 stages, and individual seed weight is determined during ripening. Fageria and Baligar (1999) reported that the timing of fertilizer-N application relates directly to FNRE and significantly affected the number of panicles and number of filled spikelets per unit area. The FNRE, panicles per unit area, and overall grain yield increased when N was applied prior to reproductive growth. However, 1000-grain weight and harvest index were not affected. Nitrogen applied late in the growing season (booting) was absorbed by the plant, but remained in the plant dry matter and did not benefit yield. The number of panicles per unit area, harvest index, and number of filled spikelets per unit area all affect overall grain yield, but the number of panicles per unit area is considered the most important yield-contributing trait (Gravois and Helms, 1992; Fageria and Baligar, 1999). However, when the number of panicles per unit area increased, the percentage of blank or sterile spikelets also increased.

Studies showing how seeding rates influence grain yield and yield components are of value to understanding how N availability influences rice grain yield because some of the same yield components are affected. Seeding rate influences the panicles per unit area, harvest index, and number of filled spikelets panicle^{-1}, and several studies have concluded that yield compensation occurs between panicle density and filled spikelets panicle^{-1} (Wells and Faw, 1978; Jones and Snyder, 1987; Gravios and Helms, 1992; Bond et al., 2008). Bond et al. (2008) reported rough rice yield, panicle density, and head rice yield were all influenced by N rate and that the effect on rice yield components could be linked to the N application time as well. Wilson et al. (1989; 1998) and Norman et al. (2013a) reported that total grain yield was affected by FNRE, which can be influenced by the application time and rate of fertilizer-N. Norman et al. (1992) reported that a single optimum preflood-N application can be delayed 21 d (panicle differentiation) beyond the current recommended application time (5-leaf stage) and not jeopardize total grain yield or harvest index, but a reduction in total biomass occurred. Norman et al. (1992) also reported that FNRE increased but native soil-N uptake decreased when preflood-N application was delayed, which resulted in no net change in total-N uptake.

Fertilizer-N application time trials with winter wheat indicate that fertilizer-N must be provided by Feekes stage 6 or yield loss will occur on N deficient soils (Alcoz et al., 1993; Edwards et al., 2009; Slaton et al., 2011; Clark et al., 2014). Mascagni et al. (1990) reported that fertilizer-N applied as late as Feekes stage 10 can significantly increase wheat yield but their results did not indicate the last growth stage that fertilizer-N can be applied to produce maximum yield potential. Feekes stage 2 is defined as the growth stage when tillering begins, while Feekes stage 6 is defined as the growth stage when tillering ceases and the first node becomes visible (Miller, 1999). Feekes growth stage 2 is comparable to rice growth stage V5, while Feekes stages 6 and 10 are similar to the R1 and R2, respectively, stages of rice (Counce et al., 2000). Clark et al. (2014) reported that applying fertilizer-N only at Feekes growth stage 3 or split applying N fertilizer at Feekes growth stages 3 and 6 maximized yield, however a reduced yield occurred due to reduced number of tillers when applying fertilizer-N in a single application at Feekes stage 6. Alcoz et al. (1993) reported that grain yield, spikes m^{-1}, grain weight m^{-1}, and straw yield are significantly affected by the time of N application. All of the yield components mentioned were significantly greater when all of the N was applied before Feekes stage 6 as compared to Feekes stage 10. Li et al. (2001a) and Abedi et al. (2011) reported that the number of spikes per unit area is set before stem elongation which correlates to Feekes stage 6. Slaton et al. (2009) reported that when fertilizer-N application time was delayed, wheat heading date was also delayed.

Several studies in corn have indicated that sidedressing fertilizer-N results in higher grain yields and FNRE as opposed to applying fertilizer-N only before planting (Miller et al., 1975; Olson et al., 1982, 1986; Welch et al., 1971). Jung et al. (1972) reported delaying N application too long results in reduced grain yield, yield components, and FNRE. For N deficient soils, delaying the sidedress-N application beyond the V8 stage, the time corn is experiencing substantial biomass accumulation, is reported to be detrimental to corn yields (Varvel et al., 1997; Binder et al., 2000). Nitrogen uptake by corn is generally greatest during late vegetative growth stages, between V8 and R1 (silking, Hanway, 1963; Russelle et al., 1983) and approximates the time of peak corn rooting depth (Hoeft et al., 2000), and accumulation of up to 70% of total aboveground N uptake (Ciampitti et al., 2013). Scharf et al. (2002) determined that the yield of corn grown in Missouri could be maximized with a single fertilizer application applied as late as the V11 stage (11 leaf collars, about 5-7 wk after emergence). When Scharf et al. (2002) delayed the fertilizer-N application until V16 and R1 (silking), minimal yield losses of only 3 and 15% were measured, respectively. The relatively low yield loss from delayed fertilizer-N application found by Scharf et al. (2002) and Gehl et al. (2005) may not be representative since corn that received no fertilizer-N produced yields that were 71% of the maximum yield produced by corn receiving fertilizer-N. Espinoza et al. (2014) reported a yield decrease when the sidedress-N application was delayed beyond the V8 growth stage. The availability of soil-N was not quantified in most of these studies, and may play an important role in how late fertilizer-N can be applied before irreversible yield loss from N deficiency begins. The number of plants and kernels per area is closely associated with the yield of corn, and the number of kernels per corn ear is a yield component that directly relates to nutrient or water stress during vegetative growth (Claassen and Shaw, 1970; Harder et al., 1982; Pandey et al., 2000).

Cotton is a non-legume fiber crop that also requires moderate fertilizer-N rates to maximize lint yields in the mid-South USA. A study in Alabama showed that fertilizer-N application could be delayed until cotton reached first-square (Mullins et al., 2003). In contrast, Mullins et al. (2003), in Mississippi, showed that fertilizer-N application could be delayed until the mid-bloom stage and still maximize yield. In contrast, from a growth stage standpoint, the first square generally occurs 5 wk after planting and flowering occurs 3 wk following the development of the first square (Oosterhuis, 1990). Boquet and Breitenback (2000) showed that N uptake occurred throughout the entire growing season, but N uptake was greatest between 49 and 71 d after planting, which coincides with the blooming and early boll set growth stages. Research has also indicated that total N accumulation is near maximum for the season at the first open boll stage (Halevy, 1976; Constable and Rochester, 1988; Li et al., 2001b). Boll ripening is the stage where N demand for cotton plants is greatest (Halevy, 1976). Yield components for cotton include total flower production, the number of flowers that develop and form bolls, boll size, and the fraction of total weight that is lint (Grimes et al., 1969). A limited N supply after the flowering growth stage can limit yield components due to decreased photosynthesis and production of assimilate (Grimes et al., 1969). Grimes et al. (1969) concluded that N availability affects several yield components (e.g., plant density per unit area, number of flowers, number or bolls, boll size, and plant height).

For the non-legume crops mentioned above, the literature provided a critical and consistent growth stage by which fertilizer-N should be applied to allow maximal yield production only for winter wheat. For corn and cotton, limited information suggested different growth stages as being critical for ensuring an adequate N supply to produce maximal yield. For rice, research has established that the yield potential is set by early-season N availability but research has not defined a specific growth stage after which fertilization with N no longer allows for maximal yield production. Delaying the preflood urea-N application and permanent flood establishment may be undesirable for reasons beyond those of plant N nutrition because delaying the flood allows additional time for weed infestation, may increase production costs associated with weed control, may accentuate some diseases and, on N deficient soils, may limit tiller formation. In years during which untimely rainfall causes wet field conditions, applying fertilizer-N to a dry soil at the 5-leaf stage, as recommended, can be challenging. Farmers are faced with applying fertilizer-N to a moist soil or waiting for the soil to dry. If urea-N is applied to a moist soil, NH_3 volatilization loss of urea-N may be substantial and result in overall low rice yields or higher fertilizer costs (Norman et al., 2009). Based on all of the research conducted on rice N availability, it may be inferred that FNRE and yield components could be unaffected or benefit when the fertilizer-N application is delayed. Delaying N application time may allow for larger seedlings with a more extensive root system that can take up fertilizer-N more rapidly and perhaps efficiently when compared to younger rice seedlings. Additional research that investigates how delaying preflood urea-N application time beyond the 4- to 5-leaf stage influences rice-N uptake and yield is needed to provide farmers with research-based answers on modern rice cultivars and hybrids, which have shorter vegetative growth periods than most of the obsolete long-season cultivars grown in prior decades.

Summary

Knowing exactly how long fertilizer-N application and flooding can be delayed without detrimentally influencing maximum rice yield potential is critical for making correct N management decisions during wet years. Research has not adequately addressed this subject (Norman et al., 1992; Slaton et al., 2015) and additional research is needed to determine how rice yield is affected and whether the available rice genotypes respond similarly. Research by Norman et al. (1992) with a single obsolete, long-season cultivar and one N rate showed that the preflood urea-N application could be delayed 21 d without yield loss. Limited research by Slaton et al. (2015) appears to confirm the yield results reported by Norman et al. (1992) but suggests different results for soil-N uptake when preflood-N is delayed. Research with wheat suggests that delaying fertilizer-N beyond the mid-vegetative growth stages limits tiller production, dry matter accumulation, and/or grain production. Research with corn suggests that delaying fertilizer-N beyond the mid-vegetative growth stages limits dry matter production and/or seed production. Based on the available literature we hypothesize that delaying the preflood urea-N application more than 21 d will result in reduced tillering, grains per unit area, and rice grain yield. The objectives of the proposed research include:

1. Evaluate the effect of preflood-N (and flood establishment time) and fertilizer-N rate on the grain yield and maturity of multiple rice cultivars that differ in growth duration (e.g., days to maturity).
2. Evaluate the effect of preflood-N (and flood establishment) time and fertilizer-N rate on the N uptake, tillering, and yield components (panicle bearing tillers, spikelet number panicle^{-1}, and percentage of filled spikelets) and harvest index of a single rice cultivar (Roy J).

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Chapter 2

Rice Aboveground-Nitrogen Content, Development, and Yield as Affected by Fertilization and Flood Timing

Abstract

Urea-N fertilizer is typically applied at the 5-leaf stage to rice (*Oryza sativa* L.) grown in a dry-seeded, delayed-flood production system. How long the preflood-N can be delayed without adverse effects on yield potential is poorly understood. Our objective was to determine the effects of delaying preflood-N application and flooding on aboveground-N content, 50% heading, yield components, and grain yield. Trials were established on silt loam soils at the Pine Tree Research Station (PTRS) and Rice Research and Extension Center (RREC) during 2015 and 2016. Urea-N was applied at 0, 45, 90, 135, and 180 kg N ha^{-1} on five to seven different dates with applications beginning near the 3-leaf stage and ranging from 127-1035 growing degree units (GDU) among five site-years (PTRS-2015a, PTRS-2015b, PTRS-2016, RREC-2015, RREC-2016). Aboveground-N content increased by 25 to 59 kg N ha^{-1} as fertilization and flooding were delayed at three of four site-years (PTRS-2015a, PTRS-2016, RREC-2015, RREC-2016) due to increased uptake of native soil-N. At the PTRS, relative grain yield of rice receiving no fertilizer-N increased from 20 to 41% of the overall maximum yield as fertilization and flooding were delayed. Fertilization and flooding time had no effect on grain yield at the RREC. At the PTRS, maximal relative yield (91%) was produced when fertilization and flooding were performed between 164 and 531 GDU and declined to 62% by 1035 GDU. Based on the results from two silt loam soils the current recommendation for the absolute deadline for applying preflood-N fertilizer is valid.

Introduction

The fertilizer-N recovery efficiency (FNRE) and yield potential of non-legume crops is generally maximized by fertilizer-N application close to the time of rapid N uptake and crop growth since this timing minimizes the period that N transformations and losses can occur. Urea-N application to a dry soil surface when rice development is at the 4-to 5-leaf stage followed by flooding the soil is a fundamental aspect of efficient N fertilization in the delayed-flood rice production system. An extensive amount of research has been conducted investigating preflood urea-N management regarding the effect of fertilizer-N source (Norman el al., 2009), soil moisture (Norman et al., 1992; Dempsey et al., 2017), rate (Roberts et al., 2011), and the time between urea-N application and flooding (Wilson, et al., 1998; Norman et al., 2009). The FNRE of urea-N applied preflood is 60 to 75% when recommended practices are followed (Norman et al., 2003). Wilson et al. (1989; 1998) and Fageria and Baligar (1999) reported that rice yield potential is set by the N availability during the vegetative rice development stages.

Despite the vast amount of research conducted on preflood-N management in the delayed-flood rice production system the literature contains limited information regarding the effect of the time or growth stage of preflood urea-N application and flood establishment on rice FNRE and grain yield. Rice begins to tiller at the 5-leaf stage and tiller formation leads to a period of rapid dry matter production (Counce et al., 2000). Research showing the effect of urea-N and flood establishment time on rice yield suggests that urea-N application could be delayed up to 3 wk beyond the 4-to 5-leaf stage without significant yield loss (Norman et al., 1992; Slaton et al., 2015). Unfortunately, the extent to which urea-N can be delayed before yield loss occurs and defining the rate of yield decline across time were not achieved in this research. The knowledge of how rice yield responds across a range of preflood urea-N application and flood times is important to determine i) whether FNRE and grain yield changes with fertilizer-N timing, ii) the critical growth stage at which grain yield loss occurs on N deficient soils, and iii) to define the rate of yield loss across time or growth stages. Interest in how long the preflood urea-N can be delayed without compromising yield has received extra attention in the mid-South USA during recent years due to the short vegetative growth duration of some modern cultivars and continuously moist soil conditions from frequent rainfall during late May and early June, when rice typically reaches the 5-leaf stage. Application of urea-N to moist soil prior to flood establishment is known to increase N loss via NH_3 volatilization and denitrification and contribute to lower grain yields (Patrick and Wyatt, 1964; Harper et al., 1983; Norman et al., 2009).

When moist field conditions persist, current recommendations suggest delaying urea-N application for about 2 wk [170 growing degree units (GDU: DD10, base temperature of 10°C) before panicle differentiation] before urea treated with an effective urease inhibitor [e.g., N-(n-butyl) thiophosphoric triamide, NBPT] should be applied to the moist soil and followed by flood establishment. The utility of this recommendation is somewhat dependent upon knowing the growth stage beyond which yield loss from early-season N deficiency is permanent, whether the cost of applying greater N rates in field conditions that facilitate N loss is feasible, and the expense associated with prolonged weed control before flooding. Although NBPT-treated urea applied to a moist soil diminishes N loss and results in greater yields than untreated urea applied to moist soil, urea-N applied to moist soil is generally recovered less efficiently than urea applied to a dry soil (Norman et al., 2009; Dempsey et al., 2017). Knowledge of how long rice can grow without supplemental N and still produce maximal yield would be beneficial for other rice production systems since irrigation water availability is an issue in many rice-growing regions (Tuong and Bouman, 2003).

A review of research with other cultivated crops failed to show a common growth stage beyond which maximum grain yield potential could no longer be achieved with efficient fertilizer-N management. The literature was consistent for winter wheat (*Triticum aestivum* L.) suggesting that delaying fertilizer-N beyond Feekes stage 5 (maximum tillering) results in lower wheat yield (Alcoz et al., 1993; Edwards et al., 2009; Slaton et al., 2011). The majority of the published literature suggests the V8 stage of corn (*Zea mays* L.) is the critical point by which fertilizer-N must be applied because N uptake is generally greatest during the late vegetative growth stages (Hanway, 1963; Russelle et al., 1983). However, Scharf et al. (2002) reported no yield loss when N was applied as late as the V11 stage. Corn yield components of kernel rows ear^{-1} and kernels row^{-1} are determined soon after the V6 stage (Harder et al., 1982; Pandey et al., 2000). Corn grain yield, yield components, and FNRE can all be compromised if N fertilization is delayed too long (Jung et al., 1972). Wheat research suggests that maximum yields can be produced when fertilizer N is applied near the time maximum tiller number and spike size has been set; where corn research suggests that maximum yields can be produced when fertilizer N is applied until mid to late vegetative growth. The consensus for all crops that require fertilizer N is that the fertilizer N must be applied while the plant is still in the vegetative growth phase and prior to the point when the plant has the highest N demand.

Our research objective was to determine the influence of preflood-N application and flood establishment time on selected yield components, aboveground-N content, and rice grain yield. The overall goal was to develop the information needed to properly manage preflood urea N when moist field conditions persist or other reasons (e.g., water availability) require a deviation from the standard recommended practices. Based on the aforementioned research with rice, wheat, and corn we hypothesized that delaying urea N for up to 3 wk past the 5-leaf stage would not change rice yield, delaying preflood-N greater than 3 wk beyond the 5-leaf stage would be detrimental to grain yield, FNRE would not be affected by urea N application time, and tillering and grains per unit area would be reduced by delayed N fertilization.

Materials and Methods

Site Description

Five field experiments were established on University of Arkansas System Division of Agriculture experiment stations in 2015 and 2016. Two experiments were established on a Dewitt silt loam (fine, smectitic, thermic Typic Albaqualf) at the Rice Research and Extension Center (RREC) near Stuttgart, AR and three experiments were established on soil mapped as a Calhoun silt loam (fine-silty, mixed, active, thermic Typic Glossaqualf) at the Pine Tree Research Station (PTRS) near Colt, AR. The experiments will be identified with the site abbreviation, year, and ‘a’ or ‘b’ to differentiate between multiple trials conducted at the same experiment station and year (RREC-2015, PTRS-2015a, PTRS-2015b, PTRS-2016 and RREC-2016). Soybean [*Glycine max* (L.) Merr.] was the previous crop grown at each site-year. Before each trial was established, composite soil samples were collected from the 0- to 10-cm and 0- to 45-cm depths for determination of soil chemical properties and fertilizer-N rate recommendations, respectively. The 0- to 10-cm samples consisted of multiple 2.5 cm o.d. soil cores composited to represent 0.25 ha sample^{-1}. Samples were oven dried, crushed, and analyzed for soil pH in a 1:2 soil:water mixture (v:v; Sikora and Kissel, 2014) and Mehlich-3 extractable nutrients (Zhang et al., 2014). The 0- to 45-cm depth samples were collected and used to determine alkaline-hydrolyzable N content for site-specific N rate recommendations (Roberts et al., 2011). The soil alkaline-hydrolyzable N concentration predicted that N rates ranging from 120 to 160 kg ha^{-1} would be the minimum urea N rate that would produce near maximal yield at each site when applied in an optimum preflood system. The recommendations for RREC-2015, RREC-2016, and PTRS (-2015a, -2015b, and -2016) were 129, 123, and 162 kg ha^{-1} respectively. The mean soil properties at each site-year are summarized in Table 2.1.

Rice Cultivars and Urea Nitrogen Rates

Each trial contained two to five rice cultivars with each trial containing at least one common cultivar, Roy J. The RREC-2015 and RREC-2016 trials included 'Clearfield (CL) 111', 'Jupiter', 'LaKast', 'RiceTec XL753' (hybrid), and Roy J. The PTRS-2015a and PTRS-2016 trials included CL111, Jupiter, LaKast, and Roy J. The PTRS-2015b trial included only Roy J and RiceTec XL753. Conventional cultivars were drill seeded at a rate of 70-80 kg ha^{-1} while hybrids were seeded at a rate of 34 kg ha^{-1}. The seeding and emergence dates of each trial are listed in Table 2.2. Insecticide seed treatments were applied to the seed of each cultivar using the labeled rate of CruiserMaxx rice seed treatment {4-(2,2-difluoro-1,3-benzodioxol-4-yl)-1H-pyrrole-3-carbonitrile [Fludioxonil (1.12%)]+ (R,S)-2-[(2,6-dimethylphenyl)-methoxyacetylamino]-propionic acid methyl ester [Mefenoxam (1.70%)] + 3-(2-chloro-1,3-thiazol-5-ylmethyl)-5-methyl-1,3,5-oxadiazinan-4-ylidene(nitro)amine [Thiamethoxam (22.61%)] [CruiserMaxx 4.06 mL kg^{-1} (7 oz cwt^{-1}), Syngenta Crop Protection, L.L.C., Greensboro, NC]}.

Individual plots were 2.3-m long and 1.8-m wide and included nine rows spaced 17.8 cm (RREC) or 19.1 cm (PTRS) apart. A 0.4-m wide, plant-free alley surrounded each individual plot. All of the cultivars were drill seeded within an area surrounded by a single levee for flooding on different dates resulting in five to seven bays per site-year. The bays assigned to fertilization and flood times were in a time ordered sequence rather than randomized. The fertilizer application and flood establishment times were performed sequentially by bay to allow for efficient water delivery, management, and drainage of irrigation water, and assumed no significant difference in rice yield potential among blocks. Each site-year contained five (RREC-2015), six (PTRS-2015a, PTRS-2015b, and RREC-2016) or seven (PTRS-2016) adjacent bays. Each cultivar was seeded in the same position within each bay (20 plots cultivar^{-1}) since the potential maturity differences would require different harvest times.

Each cultivar and fertilizer-N application time included five urea-N rates (0, 45, 90, 135, and 180 kg urea-N ha^{-1}) replicated four times as a randomized complete block design. Urea fertilizer was treated with the urease inhibitor NBPT [Agrotain Ultra, 267 g NBPT kg^{-1}, Koch Fertilizer, L.L.C., Wichita, KS] at a rate of 0.88 g NBPT kg^{-1} urea. The urea-N application times for each site-year are listed in Table 2.2. The urea-N fertilizer was broadcast onto a dry soil surface by hand (PTRS) or using a small-plot fertilizer distributor (RREC). The flood was established 1 d after urea-N application at the RREC-2015 and RREC-2016 and 2 d after urea-N application at PTRS-2015a, PTRS-2015b and PTRS-2016. Moist soil conditions caused by untimely rainfall sometimes delayed the application of urea-N or, when the forecast predicted a high probability of rain, urea-N treatments were applied a couple of days in advance of the planned interval.

In general, rice management followed practices recommended for the production of rice using the direct-seeded, delayed-flood rice production system (Hardke, 2013). Weed management was the only practice that differed among the fertilizer-N application times within each trial. Preplant-incorporated (PPI), preemergence (PRE) and postemergence (POST) herbicide applications were performed throughout the year to ensure that weeds were controlled and did not limit yield (Appendix 2.1).

Rice seedling emergence date (Table 2.2) was entered into the DD10 rice management program (e.g., DD50 for °F). The rice emergence date represents the day rice begins accumulating GDU. The DD10 program calculates GDU accumulation during the growing season as the daily average temperature (°C) [(maximum + minimum)/2] less the base temperature of 10°C. The program has daily maximum and minimum temperature thresholds that limit the maximum number of daily GDU that can be accumulated to 17.8 (Hardke et al., 2013). Daily maximum temperatures that exceed 34.4°C are entered as 34.4°C. Daily minimum temperatures less than 21.1°C are entered as 21.1°C.

Measurements

At the 2-leaf stage, a 1-m linear section within row 2 or 8 was flagged in four of the five N rates of each plot seeded with Roy J rice at the PTRS-2015a, RREC-2015, PTRS-2016, and RREC-2016. No samples were collected from PTRS-2015b. The number of plants within each flagged area was counted and, if needed, thinned to a uniform population such that the seedling density in each plot varied by less than 10%. The rice plants within each flagged section were sampled when rice receiving 135 kg N ha^{-1} reached the R2-R3 growth stage (Counce et al., 2000). All plants within each flagged section were cut 1.25 cm above the soil surface, the number of stems were counted, the aboveground biomass was oven dried at 55°C to a constant weight, weighed, ground to pass a sieve with 1-mm openings, and N concentration was determined by combustion (Campbell, 1992). Aboveground-N content was calculated as the product of aboveground biomass and N concentration. Rice fertilized with 45 kg N ha^{-1} at the

PTRS-2015a and PTRS-2016 and 180 kg N ha^{-1} at the RREC-2015 and RREC-2016 was not sampled since these N rates were considered deficient or excessive, respectively, for the site.

A second 1-m linear section in each Roy J plot fertilized with 135 kg N ha^{-1} at PTRS-2015a, PTRS-2016, RREC-2016 and 90 kg N ha^{-1} at RREC-2015 was flagged at the 2-leaf stage and seedling number was counted and thinned as described previously. At physiological maturity, the total stem number and stems with panicles were counted and plants were sampled as previously described. A 10-panicle subsample was collected to determine spikelet number panicle^{-1} and percentage of filled spikelets panicle^{-1}. Grain was threshed from the remaining panicles, stored in an air conditioned laboratory to allow seed moisture time to equilibrate, grain moisture was measured in a Dickey-John grain moisture meter (GAC-2100, Auburn, IL), and the weight of 1000 rough rice seed was recorded once the seed reached an equilibrium moisture content.

Beginning at the R2 (booting) stage, panicle emergence (heading) progress was visually estimated weekly in each plot to evaluate how delaying fertilizer N and flooding time influenced the number of days for rice panicle emergence. The relative delay in 50% rice heading was calculated by subtracting the day of year that mean 50% heading occurred for the first treatment of each cultivar and site-year combination from the day of year on which all subsequent treatments reached 50% heading. For each cultivar and site-year combination, the first treatment to reach 50% heading across all fertilization times and N rates had a relative heading delay of 0.

At maturity, the five interior rows in each plot were harvested with a small-plot combine. The moisture and weight of the harvested rice grain was determined, and grain yields were adjusted to a uniform moisture content of 120 g H_2O kg^{-1} for statistical analysis. The relative rice yield of each cultivar was calculated for each site-year by identifying the greatest numerical mean grain yield produced across the five to seven fertilization dates and dividing all other mean grain yields by this value and multiplying by 100. Relative yield removes the inherent differences in yield potential among cultivars, years and field environments placing yield on a uniform scale of 0 to 100.

Statistical Analysis

Replicate data for tiller number plant^{-1} and aboveground-N content of Roy J rice at the R2-R3 development stage were regressed across cumulative GDU at the time of fertilizer-N application for each site-year. The regression model included the linear and quadratic functions of cumulative GDU and allowed regression coefficients to depend on urea-N rate and the interaction with cumulative GDU.

Replicate data for yield components (tiller number plant^{-1}, percentage of tillers with panicles, panicles m^{-2}, spikelet number panicle^{-1}, 1000 seed grain weight, and the percentage filled spikelets) and harvest index for Roy J rice receiving 90 (RREC-2015) or 135 (RREC-2016, PTRS-15a, and PTRS-2016) kg urea-N ha^{-1} were used for regression analysis. Yield component measurements were regressed against cumulative GDU at the time of fertilizer-N application for each location (PTRS or RREC) using site-year as a random effect. The model included only the linear and quadratic functions of cumulative GDU.

The mean relative heading delay for each cultivar and N rate combination were regressed against the linear and quadratic functions of cumulative GDU at which fertilization was initiated allowing regression coefficients to depend on two urea-N rates (0 and 135 kg ha^{-1}) and their interaction with cumulative GDU. The model was run for each cultivar and included site-year as a random effect. The above process was followed because the most complex possible model that included site-year, cultivar, and N rate resulted in multiple significant interactions and required simplification to provide a meaningful general relationship. The 0 and 135 kg N ha^{-1} treatments were selected to determine how 50% heading date responded to the delay i) in flood establishment and ii) in N fertilization and flooding, respectively. Application of 135 kg N ha^{-1} approximates the single preflood-N rate that is a standard recommendation for silt loam soils that can be fertilized and flooded within 3 d. To demonstrate the full effect of N rate on relative heading delay, the regression procedure for the Roy J cultivar was also performed using all urea-N rates because Roy J was present at each site-year and had the largest number of mean values.

Mean relative grain yield data were regressed against GDU for each location (PTRS or RREC) using cultivar and site-year as random effects. The regression model included the linear and quadratic functions of cumulative GDU and allowed regression coefficients to depend on urea-N rate and the interaction with cumulative GDU. This model defines a general trend for all cultivars grown at each of the two locations that should be robust and serve as a general guide as cultivars change across time.

All regression analysis was performed using the MIXED procedure of SAS v9.4 (SAS Institute, Cary, NC). A model containing all fixed terms and their interactions was run and the most complex nonsignificant model term ($P > 0.15$) was removed sequentially until the simplest significant model was obtained. Individual regression coefficients of the final model were considered significant when $P \leq 0.10$. When appropriate, the predicted differences among preflood-N rates were evaluated using LSMEANS statements and differences within a single preflood-N rate were evaluated using ESTIMATE statements with the differences interpreted as significant when $P \leq 0.05$. The studentized residuals distribution (> ±2.5) was examined to identify and remove potential outliers and the Cook's D statistic was examined to identify and remove influential data. When appropriate, the model was refit by omitting the outlying or influential data.

The CORR procedure was used to examine the correlation between yield components and grain yield using replicate data for each site-year.

Results and Discussion

Aboveground-Nitrogen Content

The aboveground-N content of Roy J rice was measured at four of the five site-years and was a linear function of flood time at PTRS-2016 and RREC-2016 or a quadratic function of flood time at PTRS-2015a and RREC-2015 (Table 2.3; Fig 2.1). Within each site-year, aboveground-N content depended on urea-N rate with the final regression model having the same linear and quadratic coefficients resulting in parallel lines among N rates across fertilization times (Table 2.4). The predicted aboveground-N content increased incrementally as preflood urea-N rate increased, regardless of the flood timing within each site-year. The difference between the two fertilization timings that produced the minimum and maximum aboveground-N contents within each preflood urea-N rate was 59 kg N ha^{-1} for PTRS-2015a, 15 kg N ha^{-1} for RREC-2015, 25 kg N ha^{-1} for PTRS-2016, and 26 kg N ha^{-1} for RREC-2016. The aboveground-N content within 95% of the maximum predicted content was achieved when preflood-N was applied between 666 to 911 GDU at PTRS-2015a, 762 to 1035 GDU at PTRS-2016, 252 to 637 GDU at RREC-2015, and 635 to 838 GDU at RREC-2016. Thus, with the exception of RREC-2015, aboveground-N content was numerically greatest when fertilization was delayed beyond the current optimal recommended N application window (195-310 GDU).

The parallel lines among preflood-N rates indicate that any change in aboveground-N content was due to differences in soil-N uptake and not fertilizer N uptake (Table 2.4; Fig. 2.1). The aboveground-N contents of rice at PTRS-2015a, PTRS-2016 and RREC-2016 show that delaying the preflood-N fertilizer application resulted in numerically greater soil-N uptake by rice. The same trend was observed at RREC-2015 from the initial flood time until predicted aboveground-N content peaked at 432 GDU, after which time the predicted aboveground-N content declined.

Most crops obtain 50-80% of their N requirement from the soil even in cases where fertilizer N is applied at high rates (Kundu and Ladha, 1995). The percentage of the aboveground-N content contributed by soil N at the R2-R3 stage, as calculated by the difference method, tended to decrease as N rate increased and increase as flood time was delayed. The percentage of aboveground-N contributed by soil-N, averaged across N rates, ranged from 22 to 46% at PTRS-2015a, 48 to 54% at RREC-2015, 16 to 30% at PTRS-2016, 17 to 36% at RREC-2016. Increased soil-N uptake by rice from delaying the flood might be expected due to greater mineralization of soil organic-N under aerobic conditions as compared to anaerobic conditions (Patrick, 1982). However, Norman et al. (1992) reported a decrease in soil-N uptake by rice when flood establishment was delayed. Alternating aerobic and anaerobic soil conditions from periodic flush irrigation or substantial rainfall may result in increased soil-N loss via the soil-N processes of mineralization, nitrification, and denitrification and explain why an increase in N uptake by delayed flooding may not occur in some fields (Patrick and Wyatt, 1964; Patrick, 1982).

The apparent FNRE calculated using the difference method and averaged across the three applied fertilizer-N rates produced mean FNRE values of 79% for PTRS-2015a, 77% for PTRS-2016, 75% for RREC 2015, and 93% for RREC-2016. These FNRE values are typical of what others have reported for the direct-seeded, delayed-flood rice production system (Wilson et al., 1989; Norman et al., 2003). The consistent values across time indicate that FNRE was high across fertilization and flood times and differences in fertilizer-N uptake would not be responsible for lower rice yields when preflood-N is delayed. Rather, grain yield reductions due to delayed N application would likely be attributed to the effect of N uptake time on rice yield components, which include panicles area^{-1}, spikelets panicle^{-1}, the percentage of filled spikelets, and seed weight (Moldenhauer and Gibbons, 2003).

Tillering as Affected by Nitrogen Rate and Application Timing

The number of tillers plant^{-1}, as measured at the R2-R3 stage, was a linear (RREC-15) or quadratic (PTRS-2015a, PTRS-2016, and RREC-16) function of fertilization timing that depended on N rate for each of the four site-years (Table 2.3; Fig. 2.2A-D). At the RREC-2015, the predicted number of tillers plant^{-1} declined linearly as preflood urea-N fertilization was delayed and numerically and sometimes statistically increased as preflood-N rate increased (Table 2.5; Fig. 2.2B). The three sites with a quadratic response showed some fluctuation across time but, numerically, rice receiving 0 kg N ha^{-1} produced the fewest tillers plant^{-1} and rice receiving 180 kg N ha^{-1} produced the most tillers plant^{-1}. The number of tillers plant^{-1} across fertilization times showed trends to decrease for RREC-2015, increase for PTRS-2016 and RREC-2016, or the number of tillers plant^{-1} across time changed differently among the applied N rates at PTRS-2015a (Table 2.5; Fig. 2.2). The most dramatic changes in tillers plant^{-1} among preflood-N rates and across fertilization times occurred at RREC-2016, which had the lowest average seedling density (289 seedlings m^{-2}) among the four site-years (Table 2.5; Fig. 2.2). A greater number of tillers plant^{-1} is expected at low stand densities and higher preflood-N rates (Counce and Wells, 1990; Counce et al., 1992).

The results show that preflood-N is beneficial for tiller formation, but the effect of delayed fertilization is unclear from these four site-years of research (Fig. 2.2). For each site-year, rice receiving no fertilizer-N averaged 1.0 tiller plant^{-1} compared to approximately 1.4

tillers plant^{-1} for rice that received near optimal N rates (135 kg N ha^{-1}). Tiller formation is directly related to the potential number of panicles m^{-2}, which is established during vegetative growth as a function of stand density and tillering (Moldenhauer and Gibbons, 2003). The number of panicles m^{-2} is considered the most important yield-contributing component and is influenced by nutrient availability (Vlek et al., 1979; Counce et al., 1992; Gravois and Helms, 1992; Wu et al., 1998). The stand densities among the fertilization times within each site-year were uniform but density varied numerically among site-years with mean densities of 341 m^{-2} at PTRS-2015a, 372 m^{-2} at PTRS-2016, 310 m^{-2} at RREC-2015, and 289 m^{-2} at RREC-2016. Although we cannot explain the different trends in tillering among site-years, tillering is affected by a number of factors other than N availability including nutrient status and temperature (Wu et al., 1998), cultivar (Bond et al., 2008), and plant density (Schnier et al., 1990; Counce et al., 1992). Some of these factors may be partially responsible for the measured results.

Relative Rice Heading

The number of days that fertilization and flooding (Table 2.2) were delayed after the first rice at each site was fertilized was 28 d (444 GDU) at RREC-2015, 39 d (590 GDU) at PTRS-2015a and PTRS-2015b, 48 d (711 GDU) at RREC-2016, and 56 d (828 GDU) at PTRS-2016. No single model described relative heading for each of the five cultivars, but the final models were linear for Jupiter, Roy J and XL753 and quadratic for CL111 and LaKast. The R^2 value of the final models was 0.47 for LaKast, 0.70 for CL111, 0.80 for Jupiter, 0.81 for Roy J (5 N rates), and 0.87 for XL753 suggesting the model parameters accounted for a relatively large proportion of the variation in relative heading predictions for four of the five cultivars.

The delay in 50% heading of Roy J, Jupiter and XL753 cultivars receiving 0 and 135 kg N ha^{-1} increased linearly as flood establishment was delayed (Table 2.6; Fig. 2.3). For Roy J and

Jupiter, the delay in 50% heading was greater when 135 kg N ha^{-1} was applied as compared to 0 kg N ha^{-1}. The relationships for these two cultivars show that as fertilization was delayed beyond 300 to 400 cumulative GDU, fertilization with N resulted in greater heading delays compared to rice that received no fertilizer N. The Roy J relationship that included all N rates also showed that the slope values describing the delay in 50% heading increased numerically and incrementally as N rate increased (Fig. 2.3A; $R^2 = 0.81$). The relative heading delays for rice receiving 135 and 180 kg N ha^{-1} were statistically similar across fertilization times. The rate of heading delay of XL753 was the same for rice fertilized with 0 and 135 kg N ha^{-1}, but the different intercepts indicate that application of 135 kg N ha^{-1}, a near optimal rate of N, consistently delayed heading by 3 d regardless of when fertilization and flooding were initiated. LaKast and CL111 receiving no fertilizer N each exhibited a linear delay in 50% heading as flooding was delayed, but when 135 kg N ha^{-1} was applied the delay in heading was nonlinear showing that the heading delay increased as fertilization was delayed and eventually peaked at 900 GDU for LaKast and 833 GDU for CL111.

The linear slope coefficients for rice of each cultivar indicate that 50% heading was delayed by 0.018 to 0.032 d GDU^{-1} when no fertilizer N was applied (Table 2.7). In more practical terms, this amounts to about 0.3 (Jupiter) to 0.5 (LaKast) d heading delay d^{-1} of delayed fertilization when 17.8 GDU d^{-1} is used to convert thermal time to days. The predicted maximal delay in 50% heading for each cultivar receiving no fertilizer-N at 838 GDU, the only fertilization timing common to all five site-years and cultivars, was 12 d for Jupiter, 16 d for CL111, Roy J, and LaKast, and 20 d for XL753. The DD10 program used in Arkansas allows for a maximum of 17.8 GDU d^{-1} and during July and August, the two hottest months of the year, the maximum number of GDU is typically achieved on a daily basis. The maximum predicted heading delay for rice fertilized with 135 kg N ha^{-1} at 838 GDU was 16 d for Jupiter, 17 d for CL111, 18 d for LaKast, 23 d for XL753, and 26 d for Roy J. For Jupiter, Roy J, and XL753, as compared to rice receiving no fertilizer-N, the delay in 50% heading increased to 0.5 (Jupiter and XL753) to 0.7 (Roy J) d heading delay d^{-1} of delayed fertilization. The results suggest that the time of fertilization and flood establishment influence how long rice requires to head and reach maturity. Harrell et al. (2011) reported up to a 3 d heading delay from the application of 202 to 269 kg N ha^{-1} as compared to rice that received 0 to 67 kg N ha^{-1}. Norman et al. (1992) and Wells and Shockley (1978) also reported that rice heading was delayed by delaying preflood-N fertilization but the delays were generally less than 0.33 d heading delay d^{-1} of delayed fertilization. The novel aspect of our trials is that fertilization rate and delayed flooding were both evaluated across a longer period than other published research and shows that rice development is inhibited by delaying both fertilization and flooding. Our findings do suggest that rice development may be slower than predicted by the DD10 program in water management systems that include early season N fertilization but no flood is established (e.g., furrow irrigation or intermittent flooding). Additional research is warranted to examine whether a low (e.g., 35 kg N ha^{-1}) rate of supplemental-N during early vegetative growth might facilitate rice development in situations where the normal preflood-N rate and permanent flood establishment are delayed. Management practices that delay maturity are agronomically important in regards to the duration of time pests must be controlled, the duration of time irrigation is needed, and how environmental conditions influence rice grain and milling yield. Selecting the optimal fertilization and flooding time must take into consideration other aspects of crop management.

Rice Grain Yield

Rice grain yield was measured at all five site-years for two (PTRS-2015b: Roy J and XL753), four (PTRS-2015a, PTRS-2016: Roy J, LaKast, CL111, and Jupiter), or five (RREC-2015, RREC-2016: Roy J, LaKast, CL111, XL753, and Jupiter) rice cultivars. The most important aspects of the grain yield relationships are the general yield response to fertilization time, the fertilizer-N rates that produce maximal yield in response to fertilization time, and how the yields of rice that receive no fertilizer-N respond to fertilization time.

<u>Relative Yield - PTRS</u>

The actual yields of rice receiving no fertilizer N at the three PTRS site-years ranged from 2267 to 5948 kg ha^{-1} for PTRS-2015a, 2329 to 7498 kg ha^{-1} for PTRS-2015b and 2365 to 3863 kg ha^{-1} for PTRS-2016 among the represented cultivars. Based on the relative yield response prediction, rice receiving no fertilizer-N produced relative yields ranging from 20 to 41% across flood establishment times. Rice fertilized with 180 kg N ha^{-1} produced the overall maximum numerical mean yields for each cultivar at each site-year and ranged from 8454 (CL111) to 11,240 (Jupiter) kg ha^{-1} for PTRS-2015a, 9962 (Roy J) to 11,955 (XL753) kg ha^{-1} for PTRS-2015b and 8570 (CL111) to 11,014 (Jupiter) kg ha^{-1} for PTRS-2016. The maximum grain yields produced for each of the site-years are equal to or greater than the state average yields of 8264 kg ha^{-1} for 2015 and 7772 kg ha^{-1} for 2016 (USDA-NASS, 2017).

At the PTRS, relative grain yield was a quadratic function of cumulative GDU at the time of fertilization and flooding that depended on N rate (Table 2.8; Fig. 2.4A). Application of N rates lower than 135 to 180 kg N ha^{-1} produced significantly lower yields for most fertilization times, with the exception being as fertilization was delayed the amount of urea-N required to produce the maximum relative yield decreased. The relative rice yields produced by application of 180 kg N ha^{-1} were statistically similar to that produced by 135 and 90 kg N ha^{-1} when fertilization was performed between 700 and 1035 GDU and 878 and 1035, respectively. The 700, 878, and 1035 GDU accumulations are equivalent to 23, 34, and 44 d, respectively, beyond on the 5-leaf growth stage. As N rate increased, the cumulative GDU at the time of fertilization that produced the maximal relative yield for each N rate decreased. Maximal relative yields were produced by rice fertilized with 180 kg N ha^{-1} and flooded at 342 GDU (2 d beyond 5-leaf). The predicted peak relative yields for rice fertilized with 135, 90, 45 and 0 kg N ha^{-1} occurred at 465 (9 d beyond 5-leaf), 635 (20 d beyond 5-leaf), 758 (27 d beyond 5-leaf), and 750 GDU (27 d beyond 5-leaf), respectively, and gradually declined when fertilization was initiated beyond these times.

Rice receiving 180 kg N ha^{-1} produced yields that were statistically similar to the maximum predicted relative grain yield (91%) when fertilization and flooding were performed between 164 and 531 GDU (Table 2.9; Fig. 2.4A). Compared to the maximum predicted relative yield for rice fertilized with 180 kg N ha^{-1}, the overall relationship predicted that rice yields would decrease by 30% when fertilization was delayed until 1035 GDU. In contrast, the yield of rice receiving no fertilizer N gradually increased as flooding was delayed until relative yield peaked at 751 GDU, an overall relative yield increase of 21% for rice receiving no fertilizer-N. This trend agrees with aboveground-N content results for PTRS-2015a and PTRS-2016 indicating that rice was able to better utilize native soil-N when flood establishment was delayed.

The relative grain yield response to the delay in fertilization at the PTRS is consistent with the results reported by Norman et al. (1992) where grain yield was not affected when fertilization was delayed 21 d beyond the 5-leaf stage. In the PTRS experiments, grain yields did decline when fertilization and flooding were delayed beyond 21 d for rice receiving near optimal or optimal N rates. Relative grain yields became statistically different from the max for rice receiving 180 kg N ha^{-1} at 531 GDU, which is 221 to 336 GDU later than the current recommended optimal time to apply preflood-N of 195 to 310 GDU. The 221 to 336 GDU is equivalent to 13 to 20 calendar days in June based on an average accumulation of 16.6 GDU d^{-1} using June 2015 and 2016 temperature data. Grain yield began to decline even though aboveground-N content increased as fertilization was delayed suggesting that the time of N uptake influences whether the plant utilizes the N for grain or straw production. Our results are consistent with the generalization by Norman et al. (2003) that preflood-N sets the yield potential of rice grown in the direct-seeded, flood-irrigated management system used in the mid-South (Wilson et al., 1998).

Relative Yield - RREC

The actual yields of rice receiving no fertilizer N at the two RREC site-years ranged from 3034 to 6455 kg ha^{-1} for RREC-2015 and 3042 to 8930 kg ha^{-1} for RREC-2016 among the five cultivars, accounting for 46 to 54% of the predicted maximum yield produced by rice receiving fertilizer N. Rice fertilized with 180 kg N ha^{-1} produced the overall maximum numerical yields for each cultivar at each site-year and ranged from 7663 (CL111) to 12,197 (XL753) kg ha^{-1} for RREC-2015 and 8937 (Roy J) to 12,607 (XL753) kg ha^{-1} for RREC-2016 and were above the aforementioned state average yields produced each year.

The final model for relative yield at the RREC indicated relative yield was a quadratic response (Table 2.8; Fig. 2.4B) to fertilization time with the terms being included or excluded from the model using a p-value of 0.15. The final regression coefficients were regarded as significant only when the p-value was ≤ 0.10, which resulted in only the intercepts being significantly different from zero (Table 2.9). Unlike the PTRS where relative yield changed significantly across time, the final relative yield model for the RREC indicated that yields within each N rate were constant across fertilization times (Fig. 2.4B). Application of 135 to 180 kg N ha^{-1} produced maximal yields that were statistically similar despite the yields of rice fertilized with 180 kg N ha^{-1} being numerically greater (5%) than yields produced by rice fertilized with 135 kg N ha^{-1}. The relative grain yield response to the delay in fertilization at the RREC is consistent with the results reported by Norman et al. (1992). The lack of relative grain yield changes across time at the RREC as compared to the PTRS could be due to a higher soil-N availability (Table 2.1), the narrower range of fertilization times (Table 2.2), or both. If native soil-N availability is indeed partially responsible for the different rice yield trends between the silt loam soils at the RREC and PTRS, the amount of time that preflood-N can be delayed without a significant yield loss might be less for soils that are more N deficient than the Calhoun soil at the PTRS. As compared to loamy soils in the mid-South USA, rice grown on clayey soils generally requires greater fertilizer-N rates and produces lower relative yields when no fertilizer-N is applied. Additional research is needed to verify the rice yield response to N fertilization time on the most N deficient soils.

Rice Yield Components

Grain yield is the product of the panicles m^{-2}, spikelets $panicle^{-1}$, filled spikelet percentage, and grain weight (Moldenhauer and Gibbons, 2003; Jones and Snyder, 1987). Our hypothesis was that, if delayed long enough, fertilization time would influence some of these yield components since N availability influences plant growth and fertilization timing may interact with the time that each yield component is set during the plants life cycle (Counce and Wells, 1990). Rice yield components may compensate for one another to some extent to allow maximal yields to be produced across of wide range of situations (Jones and Snyder, 1987;

Gravois and Helms, 1992; Wu et al., 1998). Yield components were taken on a near optimal N rate applied to Roy J rice at each site-year and should be helpful in explaining the grain yield responses observed at the two locations (Figs. 2.5-2.6).

Yield Components - PTRS

Examination of tiller density response for the single N rate used to examine multiple yield components of Roy J rice at each site-year provides some insight to how tillering interacted with other yield components. At the PTRS, Roy J fertilized with 135 kg N ha^{-1} showed tillering decreased linearly at PTRS-2015A or increased linearly at PTRS-2016 as fertilization was delayed (Tables 2.10 and 2.11; Fig 2.5A), a similar response as measured with different samples collected from the same N rate in Fig 2.2. Although the trend (i.e., slope coefficient) for the two site-years was different, the maximum change in tillering across fertilization times was 0.17 tillers $plant^{-1}$.

The number of panicles m^{-2} was a quadratic function of fertilization timing (Tables 2.10; Fig. 2.5B). The coefficients for the linear and quadratic terms at the PTRS were identical for both years, but rice in the PTRS-16 trial produced 47 panicles m^{-2} more across fertilization times than PTRS-2015a (Table 2.11). The predicted maximum number of panicle-bearing stems at the PTRS occurred when rice was fertilized at 574 GDU with the maximum number of panicles being 344 panicles m^{-2} for PTRS-2015a and 391 panicles m^{-2} for PTRS-2016. When preflood urea was applied from 349 to 799 GDU at PTRS-2015a and 335 to 813 GDU at PTRS-2016 the panicle numbers were statistically similar to the maximum predicted value. The potential number of panicles m^{-2} is set at the time of maximum tillering. The 70-80 kg ha^{-1} seeding rates (300-350 seed m^{-2}) used to establish conventional cultivars in the direct-seeded, delayed-flood production system usually result in 150 to 300 seedlings m^{-2}. The number of panicles m^{-2}

recorded in our study was similar to those reported by Gravois and Helms (1992), Wu et al. (1998), and Fageria and Santos (2015). For these relatively high plant densities, tillering is not highly important for high rice yields, especially when 90% of the planted seed emerged. Panicle number is reportedly the most responsive yield component to N fertilization (Tanaka et al., 1964; Fageria and Santos, 2015). Vlek et al. (1979) and Miller et al. (1991) both reported that panicles m^{-2} was the most important yield component and was highly correlated with actual grain yield.

The percentage of tillers producing a panicle (effective tillers) was a quadratic response to fertilization timing at the PTRS (Table 2.10; Fig. 2.5C). The predicted maximum percentage of effective tillers was 87 and 90% when rice was fertilized at 607 GDU at PTRS-2015a and 431 GDU at PTRS-2016, respectively. The percentage of effective tillers were statistically similar to the maximum when fertilization was performed from 321 to 911 GDU for PTRS-2015a and 327 to 535 GDU at the PTRS-2016. Both site-years showed a clear trend for the percentage of tillers producing panicles to decline after some critical point during the tillering growth phase with the PTRS-2016 site showing a rapid decline (>19% decline from maximum) as fertilization was delayed beyond 1000 GDU. The sampling method we used did not allow us to differentiate between whether panicles were present on the main culm or a tiller, but it seems reasonable to assume that tillers were less likely to produce a panicle than the main culm (Moldenhauer and Gibbons, 2003).

The spikelets $panicle^{-1}$ was a positive (PTRS-2015a) or negative (PTRS-2016) linear response to fertilization time at the PTRS (Table 2.10; Fig. 2.5D). The maximum of 195 spikelets $panicle^{-1}$ was produced at 911 GDU at PTRS-2015a and 162 spikelets $panicle^{-1}$ was produced at 207 GDU at PTRS-2016. The spikelets $panicle^{-1}$ (Fig. 2.5D) and tillers $plant^{-1}$ (Fig. 2.5A) were both linear functions of fertilization time at the two PTRS site-years but the linear slope for the two measurements was always opposite suggesting that one yield component was compensating for the change in the other, similar to what was observed by Jones and Snyder (1987) and Gravois and Helms (1992). The range of spikelets panicle^{-1} in our study was comparable to that reported by Counce and Wells (1990). The number of spikelets panicle^{-1} is determined at panicle differentiation (Moldenhauer and Gibbons, 2003) and has been shown to be positively and linearly related to fertilizer-N rate (Counce et al., 1992).

The percentage of filled spikelets responded quadratically to fertilization time at PTRS-2015a and PTRS-2016 (Table 2.10; Fig. 2.5E). The predicted maximal percent of filled spikelets was 86% for PTRS-2015a and 94% for PTRS-2016 when fertilization was performed at 528 GDU. The greatest fluctuation in percentage filled spikelets occurred at the PTRS-2016 with a range of 83 to 94%. The lowest predicted percent filled spikelets occurred for the latest fertilization time for both site-years. The percentage of filled spikelets were statistically similar to the maximum when fertilization occurred from 321 to 685 GDU (PTRS-2015a) and 207 to 685 GDU (PTRS-2016). According to Vlek et al. (1979) the percentage of filled spikelets is set during the flowering stage suggesting that delayed N fertilization would not directly influence this yield component. The percent filled spikelets in our study was comparable to that reported by Wu et al. (1998) and Fageria and Santos (2015).

Rough rice grain weight was a quadratic function of fertilization time at PTRS-2015a and PTRS-2016 (Table 2.10; Fig. 2.5F). Maximal seed weight occurred when fertilization was performed at 436 GDU for each site-year with seed weight consistently being 4.4 mg seed^{-1} greater for PTRS-2015a than PTRS-2016. Seed weight fluctuated by 2.3 mg seed^{-1} at PTRS-2015a and 3.6 mg seed^{-1} at PTRS-2016 with the predicted lowest grain weight occurring for the latest fertilization times. Seed weights statistically similar to the maximum occurred at the PTRS when fertilization was performed between 321 to 580 GDU (PTRS-2015a) and 207 to 580 (PTRS-2016). The seed weight range of our data is similar to that reported by Jones and Snyder (1987), Gravois and Helms (1992), Bond et al. (2008), and Mahajan et al. (2011).

At the PTRS, grain yield was affected by fertilization time and multiple yield components were correlated with actual grain yield. For PTRS-2015 (n = 24), seed weight (P = 0.049, r = 0.41) and the percentage of filled spikelets were positively correlated with actual grain yield. Cumulative GDU at fertilization was negatively correlated with seed weight, panicles m^{-2}, and percentage filled spikelets and positively correlated with spikelets $panicle^{-1}$. For PTRS-2016 (n = 28), the percentage of panicle producing tillers (r = 0.76), percentage filled spikelets (r = 0.61), seed weight (r = 0.60), panicles m^{-2} (r = 0.43), and spikelets $panicle^{-1}$ (r = 0.40) were all positively and significantly ($P \leq 0.10$) correlated with actual grain yield and, all but panicles m^{-2}, were significantly and negatively correlated with cumulative GDU (r = -0.54 to -0.77) at fertilizer application time. The different (i.e., positive vs negative vs no effect) correlations found for spikelets $panicle^{-1}$ and panicles m^{-2} between site-years indicate that these yield components likely changed to compensate for each other. The elasticity of these yield components is well documented in the literature (Jones and Snyder, 1987; Gravois and Helms 1992). The only consistent yield component responses for the two PTRS site-years were strong negative correlations for seed weight (r = -0.73 and -0.85) and percentage of filled spikelets (r = -0.42 and -0.54) across cumulative GDU at fertilization. Both of these negative correlations suggest delayed N fertilization and flooding compromises the plants ability to fertilize and fill grain during ripening. Seed weight is largely determined during the grain fill phases (Vlek et al., 1979; Moldenhauer and Gibbons, 2003), but our results suggest that early season N availability influences both of these yield components. Early season N availability is critical for starch and sugar accumulations in the leaf and culm, which account for 20 to 40% of crop yield (Yoshida, 1972) from sugar translocation and its influence on grain development (Turner and Jund, 1993). According to Counce et al. (1992) rice seed weight usually decreases as fertilizer-N rate increases.

Yield Components - RREC

The final models describing rice growth and yield component responses to fertilization time at RREC-2015 and RREC-2016 were considerably different, although not statistically compared, than the results described for PTRS-2015 and PTRS-2016 (Tables 2.10 and 2.11). Despite the different response trends between the different locations, like the PTRS, the results for several measurements at the RREC shared common trends between years. Yield components at RREC-2015 and RREC-2016 were evaluated on Roy J rice that received 90 and 135 kg N ha^{-1}, respectively. Tillers $plant^{-1}$ (Fig. 2.6A), panicles m^{-2} (Fig. 2.6B), and seed weight (Fig. 2.6F) all showed no change across fertilization times, but the average values, as indicated by the intercepts (Table 2.11), for each parameter differed between years. For RREC-2015, plants fertilized with 90 kg N ha^{-1} contained an average of 1.22 tillers $plant^{-1}$, 304 panicles m^{-2}, and seed weighed 22.0 mg $seed^{-1}$. For RREC-2016, plants fertilized with 135 kg N ha^{-1} contained an average of 1.27 tillers $plant^{-1}$, 374 panicles m^{-2}, and seed weighed 20.1 mg $seed^{-1}$.

The percentage of tillers bearing panicles was a quadratic function of N fertilization time for both site years but the response varied between the two years (Tables 2.10 and 2.11; Fig 2.6C). The percentage of effective tillers ranged from 85 to 88% across fertilization times for RREC-2015 with no significant difference across flood times (Fig 2.6C). In contrast, for the RREC-2016, the percentage of tillers bearing panicles declined gradually across fertilization times with a maximum of 91% at the first fertilization time (127 GDU) to a low of 87% at the final fertilization time. A similar trend was observed for both site-years at the PTRS (Fig. 2.5C).

The number of spikelets panicle^{-1} was a quadratic function of fertilization time with both years sharing common intercept, linear and quadratic coefficients (Table 2.10; Fig. 2.6D). The predicted maximum number of spikelets panicle^{-1} occurred at the initial fertilization times for the RREC-2015 (154 spikelets panicle^{-1} at 252 GDU) and RREC-2016 (167 spikelets panicle^{-1} at 127 GDU) and declined to the lowest value of 144 spikelets panicle^{-1} at 516 GDU before increasing with further delays in N fertilization. The percentage of filled spikelets was a positive linear function of fertilization time (Tables 2.10-2.11; Fig. 2.6E). The percentage of filled spikelets increased from 84 to 90% as fertilization was delayed for RREC-2015, representing a significant change from the first to the last fertilization times. For RREC-2016, the linear coefficient was not statistically different from zero and averaged 90% across fertilization times.

For the two site-years at the RREC, only spikelets panicle^{-1} was significantly and positively correlated (P = 0.070, r = 0.39) with actual grain yield for RREC-2016 (n = 24). The lack of significant correlations for the two RREC site-years is not surprising since grain yield (Fig. 2.4B) and most yield components (Fig. 2.6) were constant across fertilization times. For RREC-2015 (n = 20), the percentage of filled spikelets (P = 0.001, r = 0.71), seed weight (P = 0.088, r = -0.39), and the average number of spikelets panicle^{-1} (P = 0.044, r = -0.46) were significantly correlated with the cumulative GDU at fertilization. Different yield components including panicles m^{-2} (P = 0.027, r = -0.46) and the percentage of panicle producing tillers (P = 0.004, r = -0.58) were negatively correlated with cumulative GDU at the time of fertilization forRREC-2016. Overall, the RREC correlations show no distinct trend for yield component response to fertilization time.

Conclusions

Our research examined the yield response of multiple rice cultivars grown in the direct-seeded, delayed-flood production system to fertilizer-N application rate and time on two different silt loam soils. The unique aspect of this research is fertilization and flood establishment were delayed beyond 21 d after the 5-leaf stage, which was the maximum delay reported in published research. The results from both sites indicate that rice heading and maturity are delayed by delaying the flood, delaying N fertilization time, and increasing N rate. Delaying fertilization and flooding had both positive and negative effects on rice N uptake and grain yield. Delaying flood establishment resulted in greater soil-N uptake by rice in three of four site-years. Increased rice uptake of soil-N by delaying flooding may be a significant finding for production systems that have limited fertilizer-N resources such as organic production and allow greater yields to be produced with less fertilizer N. Delaying N fertilization and flooding until 838 GDU at the RREC had no significant effect on rice yield. In contrast, delaying N fertilization and flooding beyond 531 GDU at the PTRS on a soil with slightly less available soil-N resulted in significant yield declines for the N rates that produced maximal grain yield. Although the exact reasons for the different responses between soils are not known, the two soils have slightly different native soil-N availabilities which may play an important role influencing how long fertilizer N can be delayed before irreversible yield loss occurs. Different soil-N availabilities among research studies with corn may explain in part why the literature lacks a consensus decision about how late fertilizer N can be applied to corn before yield loss occurs. Regardless of the crop, soils with less available N are more likely to suffer from irreversible yield loss when fertilizer-N application is delayed beyond some critical point.

The current recommended time to apply preflood urea-N to a direct-seeded, delayed-flood system is when rice reaches the 4- to 5-leaf growth stage, which corresponds to 195 to 310 GDU. The current final fertilizer-N application time recommended for the five cultivars averaged 435 GDU and ranged from 348 to 502 GDU. The different final fertilizer N application times among cultivars is based on the predicted time of 1.25 cm internode elongation (cultivar range of 635 to 789 GDU), which is closely associated with panicle differentiation. Our results indicate that rice grain yield sometimes declines when fertilization and flooding were delayed beyond 531 GDU. For the five cultivars included in this research, the 531 GDU threshold is 221 to 336 GDU, approximately 13 to 20 d, beyond the current recommended optimal period to apply preflood-N and 96 GDU (approximately 6 d) beyond the average final recommended time to apply preflood-N. The current recommendation in Arkansas is slightly conservative to ensure fertilizer application management does not compromise crop yield. Based on these results the absolute cutoff date by which fertilizer-N should be applied is a valid recommendation, but a longer fertilization delay may be possible on soils with sufficient soil-N availability.

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Tables

Table 2.1. Selected soil property means of five N application timing trials conducted on silt loam soils.

Site-year†	Soil pH‡	SOM§	Mehlich-3 extractable nutrients¶ P	K	Ca	Mg	S	Zn	AH-N#
		g kg^{-1}	---mg kg^{-1}---						
PTRS-2015a	7.3	2.3	22	100	1636	341	7	2.7	55
PTRS-2015b	7.5	2.2	28	100	1655	305	8	2.0	75
PTRS-2016	7.8	2.1	32	108	2183	350	16	1.6	69
RREC-2015	6.6	1.6	23	94	1035	142	11	4.2	100
RREC-2016	7.1	2.0	23	114	1628	149	6	1.4	108

† RREC, Rice Research and Extension Center located in Stuttgart, AR; PTRS, Pine Tree Research Station located near Colt, AR.

‡ Soil pH determined in a 1:2 soil:water mixture using soil samples collected from the 0-10 cm depth (Sikora and Kissel, 2014).

§ SOM, soil organic matter. Determined by loss on ignition using soil samples collected from the 0-10 cm depth (Schulte and Hopkins, 1996).

¶ Phosphorus, K, Ca, Mg, S, and Zn extracted with Mehlich-3 solution using soil samples collected from 0-10 cm depth and determined by inductively coupled plasma atomic emission spectroscopy (ICP–AES, Arcos-160 SOP, Spectro, NJ; Zhang et al., 2014).

AH-N, Alkaline-hydrolyzable N (AH-N). Determined using soil samples taken from the 0-45 cm depth (Roberts et al., 2011).

Table 2.2. Selected agronomically important dates including planting, emergence, and urea-N fertilizer application with the corresponding cumulative growing degree units, at five site-years.

Site-year†	Planting date	Emergence date	Urea-N applied‡						
			Time 1	Time 2	Time 3	Time 4	Time 5	Time 6	Time 7
			----------------------------------Month/day (Cumulative growing degree units)-----------------------------						
PTRS-2015a	04/08	04/19	05/23 (321)	06/04 (464)	06/08 (523)	06/17 (680)	06/23 (778)	07/01 (911)	--
PTRS-2015b	05/01	05/09	05/23 (164)	06/04 (307)	06/08 (366)	06/17 (523)	06/23 (621)	07/01 (754)	--
PTRS-2016	04/05	04/22	05/11 (207)	05/23 (312)	06/08 (542)	06/15 (664)	06/22 (789)	06/29 (913)	07/06 (1035)
RREC-2015	04/30	05/09	05/28 (252)	06/04 (339)	06/14 (456)	06/17 (556)	06/25 (696)	--	--
RREC-2016	04/23	05/01	05/12 (127)	05/23 (226)	06/01 (360)	06/09 (482)	06/20 (677)	06/29 (838)	--

† RREC, Rice Research and Extension Center located in Stuttgart, AR. PTRS, Pine Tree Research Station located near Colt, AR.
‡ Flood established 1 d after fertilizer application at RREC and 2 d after fertilizer application at PTRS.

Table 2.3. Analysis of covariance p-values for aboveground-N content and tillers plant^{-1} for Roy J rice as affected by N rate (NR) regressed across cumulative growing degree units (GDU) at fertilizer application time as defined by the final model for four trials conducted at the Pine Tree Research Station (PTRS) and the Rice Research and Extension Center (RREC) in 2015 and 2016.

Site-year	Source of variation	df†	N Content	Tillers plant^{-1}
			-------------------*P*-value------------------	
PTRS-2015a	NR	3	<0.0001	0.0014
	GDU	1	0.0004	NS‡
	GDU × NR	3	NS‡	0.0104
	GDU × GDU	1	0.0138	NS
	GDU × GDU × NR	3	NS	0.0513
PTRS-2016	NR	3	<0.0001	NS
	GDU	1	<0.0001	NS
	GDU × NR	3	NS	<0.0001
	GDU × GDU	1	NS	NS
	GDU × GDU × NR	3	NS	<0.0001
RREC-2015	NR	3	<0.0001	<0.0001
	GDU	1	0.0135	<0.0001
	GDU × NR	3	NS	NS
	GDU × GDU	1	0.0057	NS
	GDU × GDU × NR	3	NS	NS
RREC-2016	NR	3	<0.0001	0.0543
	GDU	1	<0.0001	NS
	GDU × NR	3	NS	0.0034
	GDU × GDU	1	NS	0.0004
	GDU × GDU × NR	3	NS	NS

† The df for the final model is the sum of the df for each model term (intercept, linear, and quadratic) listed as a source of variation.
‡ NS, not significant (*P*>0.15) in the final model.

Table 2.4. Regression coefficients for aboveground-N content of Roy J rice as affected by N rate regressed across cumulative growing degree units at fertilizer application time defined by the final model for trials conducted at the Pine Tree Research Station (PTRS) and Rice Research and Extension Center (RREC) in 2015 and 2016.

		Parameter estimates†					
		2015 or 2015a			2016		
Location	N rate	Intercept	Linear	Quadratic	Intercept	Linear	Quadratic
	kg N ha^{-1}	---Coefficients---					
PTRS	0	-49.9	0.297	-0.00016	11.9	0.0298	NS‡
	45	--§	--	--	--	--	--
	90	25.6¶	0.297	-0.00016	82.6	0.0298	NS
	135	58.1	0.297	-0.00016	121.2	0.0298	NS
	180	79.2	0.297	-0.00016	138.3	0.0298	NS
	SE	24.3	0.081	0.00007	6.7	0.0072	NS
	R^2		0.83			0.85	
RREC	0	31.0	0.19	-0.00022	10.1	0.037	NS
	45	66.4	0.19	-0.00022	48.7	0.037	NS
	90	94.0	0.19	-0.00022	104.4	0.037	NS
	135	134.2	0.19	-0.00022	128.5	0.037	NS
	180	--	--	--	--	--	--
	SE	16.3	0.073	0.00008	5.8	0.0087	NS
	R^2		0.89			0.86	

† Linear ($y = a + bx$) and quadratic ($y = a + bx + cx^2$) models where y = aboveground-N content (kg N ha^{-1}), x = fertilizer application time expressed as cumulative growing degree units, a = intercept coefficient, b = linear slope coefficient, and c = quadratic slope coefficient.

‡ NS, not significant (P>0.15) in the final model.

§ Aboveground-N content was not measured.

¶ Coefficient is not significantly different than 0 (P>0.10).

Table 2.5. Regression coefficients for tiller production (tillers plant^{-1}) of N-content samples as affected by N rate regressed across cumulative growing degree units at fertilizer application time defined by the final model for Roy J at four site-years at the Pine Tree Research Station (PTRS) and Rice Research and Extension Center (RREC) in 2015 and 2016.

		Parameter estimates†					
		2015 or 2015a			2016		
Location	N rate	Intercept	Linear	Quadratic	Intercept	Linear	Quadratic
	kg N ha^{-1}	Coefficients					
PTRS	0	0.47¶	0.00165¶	-1.22×10^{-6} ¶	0.82	-0.00012	2.63×10^{-7}
	45	--§	--	--	--	--	--
	90	1.62	-0.00139¶	9.65×10^{-7} ¶	0.82	0.00058	-2.73×10^{-7}
	135	1.94	0.00198¶	1.33×10^{-6} ¶	0.82	0.00119	-6.62×10^{-7}
	180	3.04	-0.00499	3.22×10^{-6}	0.82	0.00161	-1.07×10^{-7}
	SE	0.45	0.00157	1.24×10^{-6}	0.058	0.00024	$<1.00\times10^{-7}$
	R^2		0.34			0.60	
RREC	0	1.21	-0.00050	NS‡	1.10	-0.00098	1.45×10^{-6}
	45	1.37	-0.00050	NS	1.21	-0.00074	1.45×10^{-6}
	90	1.40	-0.00050	NS	1.40	-0.00072	1.45×10^{-6}
	135	1.57	-0.00050	NS	1.33	-0.00017¶	1.45×10^{-6}
	180	--	--	--	--	--	--
	SE	0.068	0.00012	NS	0.106	0.00041	$<1.00\times10^{-6}$
	R^2		0.50			0.31	

†Linear ($y = a + bx$) and quadratic ($y = a + bx + cx^2$) models where y = tillers tillers plant^{-1}, x = fertilizer application time expressed as cumulative growing degree units, a = intercept coefficient, b = linear slope coefficient, and c = quadratic slope coefficient.
‡ NS, not significant (P>0.15) in the final model.
§ Tiller number not measured.
¶ Coefficient is not significantly different than 0 (P>0.10).

Table 2.6. Analysis of covariance p-values for relative 50% heading delay as affected by two selected N rates (NR) or all N rates (Roy J) regressed across cumulative growing degree units (GDU) at the time of fertilizer application as defined by the final model for five cultivars grown at the Pine Tree Research Station (PTRS) and Rice Research and Extension Center (RREC) in 2015 and 2016.

Cultivar†	Source of variation	df‡	Relative heading delay
			---------*P* value---------
CL111	NR	1	NS§
	GDU	1	NS
	GDU × NR	1	<0.0001
	GDU × GDU	1	NS
	GDU × GDU × NR	1	<0.0001
Jupiter	NR	1	0.0009
	GDU	1	NS
	GDU × NR	1	<0.0001
	GDU × GDU	1	NS
	GDU × GDU × NR	1	NS
LaKast	NR	1	NS
	GDU	1	NS
	GDU × NR	1	<0.0001
	GDU × GDU	1	NS
	GDU × GDU × NR	1	0.0142
XL753	NR	1	0.0028
	GDU	1	<0.0001
	GDU × NR	1	NS
	GDU × GDU	1	NS
	GDU × GDU × NR	1	NS
Roy J (All N rates)	NR	4	0.0696
	GDU	1	NS
	GDU × NR	4	<0.0001
	GDU × GDU	1	NS
	GDU × GDU × NR	4	NS

† Regression analysis included either two (0 and 135 kg N ha^{-1}) N rates for four cultivars or five N rates (0, 45, 90, 135 and 180 kg N ha^{-1}) for Roy J. The df indicates whether two or five N rates were used in the model.

‡ The df for the final model is the sum of the df for each model term (intercept, linear, and quadratic) listed as a source of variation.

§ NS, not significant (P>0.15) in the final model.

Table 2.7. Regression coefficients for relative 50% heading delay as affected by N rate regressed across growing degree units at the time of fertilizer application defined by the final model for five cultivars grown at the Pine Tree Research Station (PTRS) and Rice Research and Extension Center (RREC) in 2015 and 2016.

		Parameter estimates†		
Cultivar	N rate	Intercept	Linear	Quadratic
	kg N ha^{-1}	---------------------Coefficients------------------------		
CL111	0	-3.9	0.028	-0.0000054‡
	135	-3.9	0.050	-0.0000300
	SE	1.55	0.0059	0.0000054
	R^2		0.70	
Jupiter	0	-2.8‡	0.018	NS§
	135	-7.0	0.028	NS
	SE	1.57	0.0014	--
	R^2		0.80	
LaKast	0	-6.0	0.032	-0.0000066§
	135	-6.0	0.054	-0.0000300
	SE	2.51	0.0102	0.0000093
	R^2		0.47	
XL753	0	-4.8	0.029	NS
	135	-1.2‡	0.029	NS
	SE	1.54	0.0025	--
	R^2		0.87	
Roy J (All N rates)	0	-2.6‡	0.022	NS
	45	-5.2	0.028	NS
	90	-5.1	0.031	NS
	135	-6.6	0.039	NS
	180	-5.3	0.038	NS
	SE	1.68	0.0002	--
	R^2		0.81	

† Linear ($y = a + bx$) and quadratic ($y = a + bx + cx^2$) models where y = 50% heading delay (days), x = accumulated growing degree units at the time of fertilizer application, a = intercept coefficient, b = linear slope coefficient, and c = quadratic slope coefficient.
‡ Coefficient is not significantly different than 0 (P>0.10).
§ NS, not significant (P>0.15) in the final model.

Table 2.8. Analysis of covariance p-values for relative rice grain yield as affected by N rate (NR) regressed across cumulative growing degree units (GDU) at fertilizer application time as defined by the final model for three site-years at the Pine Tree Research Station (PTRS) and two site-years at the Rice Research and Extension Center (RREC) in 2015 and 2016.

Location	Source of variation	df†	Relative yield
			-------*P* value-------
PTRS	NR	4	<0.0001
	GDU	1	NS‡
	GDU × NR	4	<0.0001
	GDU × GDU	1	<0.0001
	GDU × GDU × NR	4	NS
RREC	NR	4	<0.0001
	GDU	1	0.4852
	GDU × NR	4	NS
	GDU × GDU	1	NS
	GDU × GDU × NR	4	<0.0001

† The df for the final model is the sum of the df for each model term (intercept, linear, and quadratic) listed as a source of variation.
‡ NS, not significant (P>0.15) in the final model.

Table 2.9. Regression coefficients for relative rice grain yield as affected by N rate regressed across cumulative growing degree units at fertilizer application time as defined by the final model for three site-years at the Pine Tree Research Station (PTRS) and two site-years at the Rice Research and Extension Center (RREC) in 2015 and 2016.

		Parameter estimates†		
Location	N rate	Intercept	Linear	Quadratic
	kg N ha^{-1}	------------------------Coefficients	---------------------	
PTRS	0	7.3‡	0.0901	-0.0000600
	45	24.1‡	0.0909	-0.0000600
	90	48.4	0.0762	-0.0000600
	135	70.2	0.0558	-0.0000600
	180	83.7	0.0410	-0.0000600
	SE	5.3	0.0107	0.0000083
	R^2		0.61	
RREC	0	47.3	-0.0084‡	0.0000190‡
	45	64.7	-0.0084‡	0.0000150‡
	90	79.4	-0.0084‡	0.0000066‡
	135	92.3	-0.0084‡	-0.0000059‡
	180	97.3	-0.0084‡	-0.0000083‡
	SE	3.7	0.0109	0.0000120
	R^2		0.68	

† Linear ($y = a + bx$) and quadratic ($y = a + bx + cx^2$) models where y = grain yield (kg ha^{-1}), x = cumulative GDU at the time of fertilizer application, a = intercept coefficient, b = linear slope coefficient, and c = quadratic slope coefficient.
‡ Coefficient is not different than 0 (P>0.10).

Table 2.10. Analysis of covariance p-values for yield components as affected by year (Yr) regressed across cumulative growing degree units (GDU) at fertilizer application time as defined by the final model for Roy J rice grown at the Pine Tree Research Station (PTRS) and Rice Research and Extension Center (RREC) in 2015 and 2016.

Location	Source of variation	df†	Tillers plant^{-1}	Panicles m^{-2}	Effective tillers‡	Spikelets panicle^{-1}	% Filled spikelets	Seed weight
			--*P* value--					
PTRS	Yr	1	0.0689	0.0083	0.0066	0.0365	0.0177	<0.0001
	GDU	1	NS§	0.0266	NS	NS	0.1826	0.1986
	GDU × Yr	1	0.0860	NS	0.0025	0.0147	NS	NS
	GDU × GDU	1	NS	0.0181	0.0007	NS	0.0910	0.0433
	GDU × GDU × Yr	1	NS	NS	NS	NS	NS	NS
RREC	Yr	1	0.0642	0.0006	NS	NS	0.0193	0.0549
	GDU	1	NS	NS	NS	0.0333	NS	NS
	GDU × Yr	1	NS	NS	0.0182	NS	0.1218	NS
	GDU × GDU	1	NS	NS	NS	0.0401	NS	NS
	GDU × GDU × Yr	1	NS	NS	0.0295	NS	NS	NS

† The df for the final model is the sum of the df for each model term (intercept, linear, and quadratic) listed as a source of variation.
‡ Effective tillers, the percentage of tillers producing a panicle.
§ NS, not significant (*P*>0.15) in the final model.

Table 2.11. Regression coefficients for yield components as affected by year regressed across cumulative growing degree units at fertilizer application time as defined by the final model for Roy J rice grown at the Pine Tree Research Station (PTRS) and Rice Research and Extension Center (RREC) in 2015 and 2016.

		Parameter estimates†					
		2015 or 2015a			2016		
Location	Yield component†	Intercept	Linear	Quadratic	Intercept	Linear	Quadratic
		Coefficients					
PTRS	Tillers plant^{-1}	1.36	-0.00022‡	NS§	1.11	0.00021	NS
	SE	0.098	0.00015	--	0.060	0.00010	--
	R^2			0.54			
	Panicles m^{-2}	229	0.402	-0.00035	276	0.402	-0.00035
	SE	45.3	0.152	0.00012	41.0	0.152	0.00012
	R^2			0.75			
	Effective tillers	65	0.0728	-0.00006	79	0.0517	-0.00006
	SE	5.2	0.0156	0.000012	4.2	0.0151	0.000012
	R^2			0.90			
	Spikelets pan^{-1}	115	0.0878	NS	170	-0.0385	NS
	SE	18.2	0.0283	--	12.8	0.0184	--
	R^2			0.69			
	PF spikelets¶	75	0.04223‡	-0.000040	82	0.04223‡	-0.000040
	SE	8.7	0.02924	0.000023	7.9	0.02924	0.000023
	R^2			0.61			
	Seed weight	23.5	0.0087‡	-0.00001	19.1	0.0087‡	-0.00001
	SE	1.88	0.0063	5.04×10^{-6}	1.69	0.0063	5.04×10^{-6}
	R^2			0.88			
RREC	Tillers plant^{-1}	1.22	NS	NS	1.27	NS	NS
	SE	0.019	--	--	0.017	--	--
	R^2			0.33			
	Panicles m^{-2}	304	NS	NS	374	NS	NS
	SE	10.0	--	--	9.1	--	--
	R^2			0.75			
	Effective tillers	93	-0.0412	0.00005	93	-0.0154‡	9.79×10^{-6}‡
	SE	2.4	0.0124	0.000015	2.4	0.0120	0.000012
	R^2			0.83			
	Spikelets pan^{-1}	184	-0.1568	0.00015	184	-0.1568	0.00015
	SE	13.2	0.0611	0.00006	13.2	0.0611	0.00006
	R^2			0.61			
	PF spikelets¶	81	0.01221	NS	90.0	0.00074‡	NS
	SE	2.5	0.00511	--	1.5	0.00296	--
	R^2			0.68			
	Seed weight	22.0	NS	NS	20.1	NS	NS
	SE	0.65	NS	--	0.59	--	--
	R^2			0.35			

† Linear ($y = a + bx$) and quadratic ($y = a + bx + cx^2$) models where y = tillers plant^{-1}, x = fertilizer application time expressed as cumulative growing degree units, a = intercept coefficient, b = linear slope coefficient, and c = quadratic slope coefficient.
‡ Coefficient is not significantly different than 0 (P>0.10).
§ NS, not significant (P>0.15) in the final model.
¶ PF Spikelets, % filled spikelets; Spikelets pan^{-1}, Spikelets panicle^{-1}.

Figures

Fig. 2.1. Aboveground-N content at the R2-R3 stage for Roy J rice receiving four different N rates regressed across cumulative growing degree units at the time of N fertilization for four site-years at the Pine Tree Research Station (PTRS) and Rice Research and Extension Center (RREC). Regression coefficients are listed in Table 2.4.

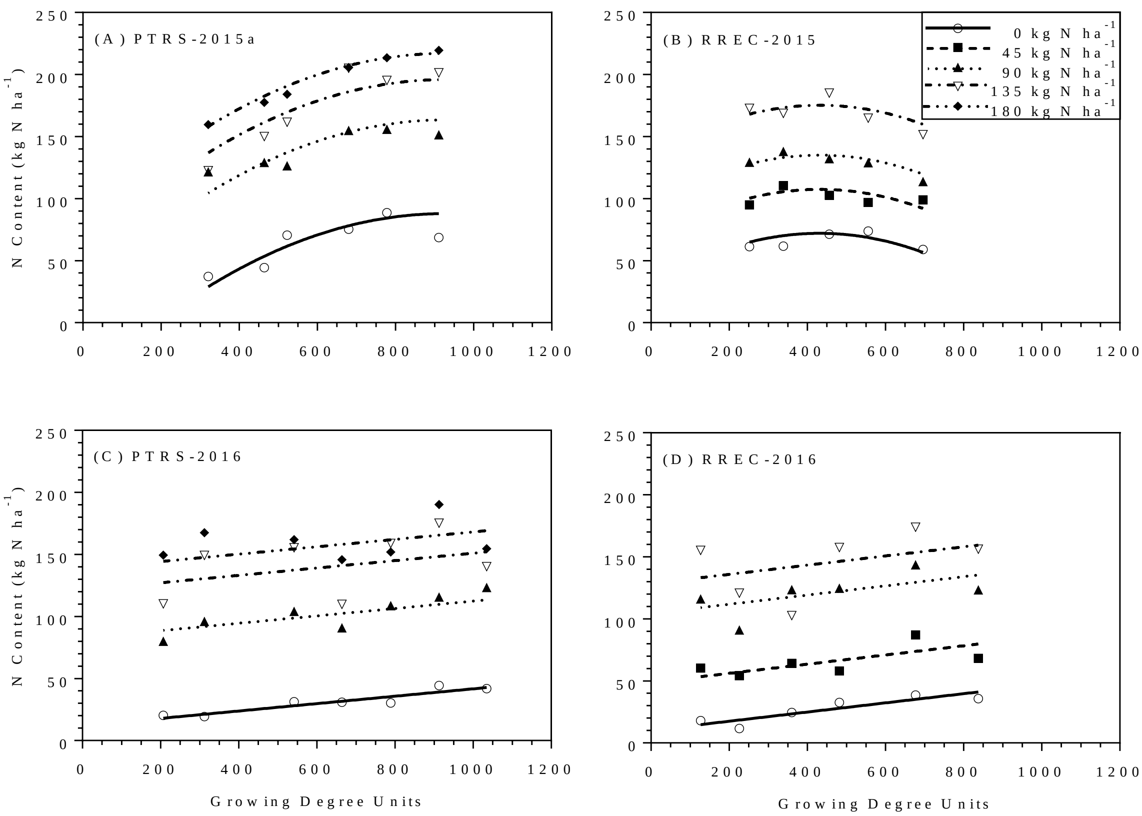


Fig. 2.2. Tillers plant^{-1} at the R2-R3 stage for Roy J rice receiving four different N rates regressed across cumulative growing degree units at the time of N fertilization for four site-years at the Pine Tree Research Station (PTRS) and Rice Research and Extension Center (RREC) in 2015 or 2016. Regression coefficients are listed in Table 2.5.

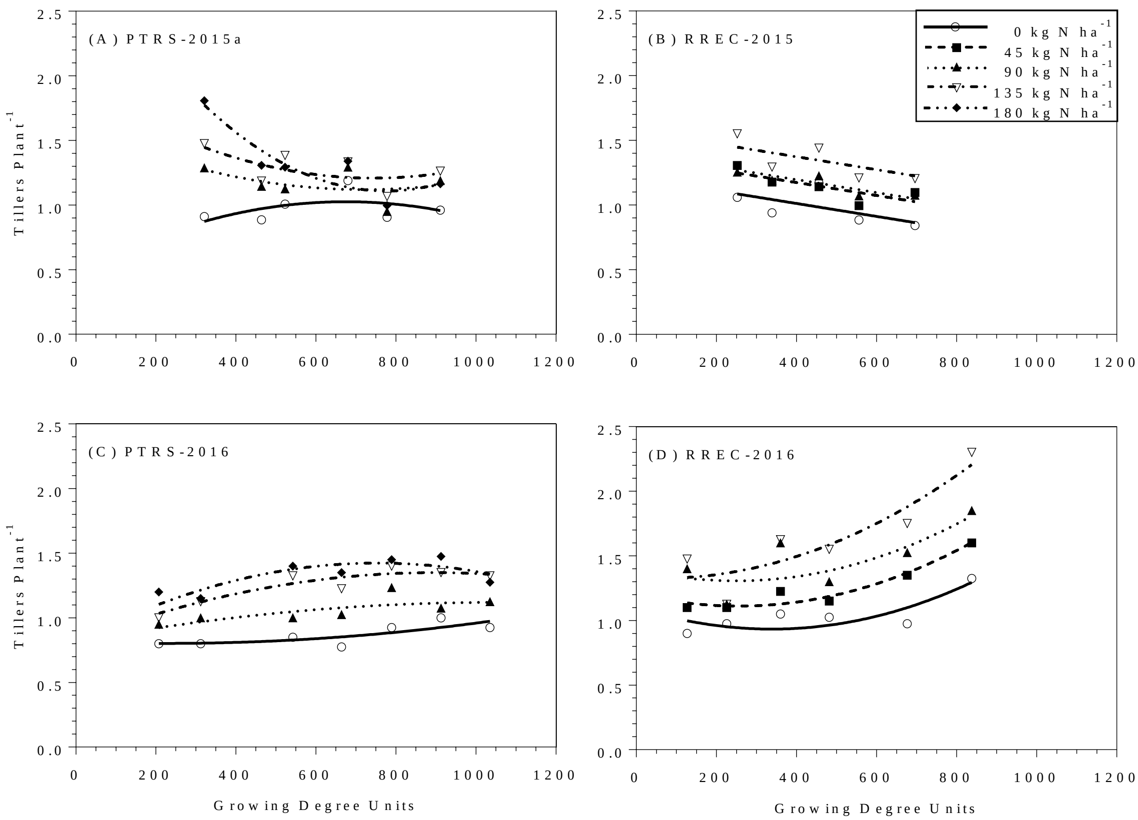


Fig. 2.3. The relative delay in 50% heading for (A) Roy J, (B) LaKast, (C) CL111, (D) Jupiter, and (E) XL753 rice cultivars receiving two or five (Roy J) different N rates regressed across cumulative growing degree units at the time of N fertilizer application as defined by the final model where site-year was a random effect. Regression coefficients are listed in Table 2.7.

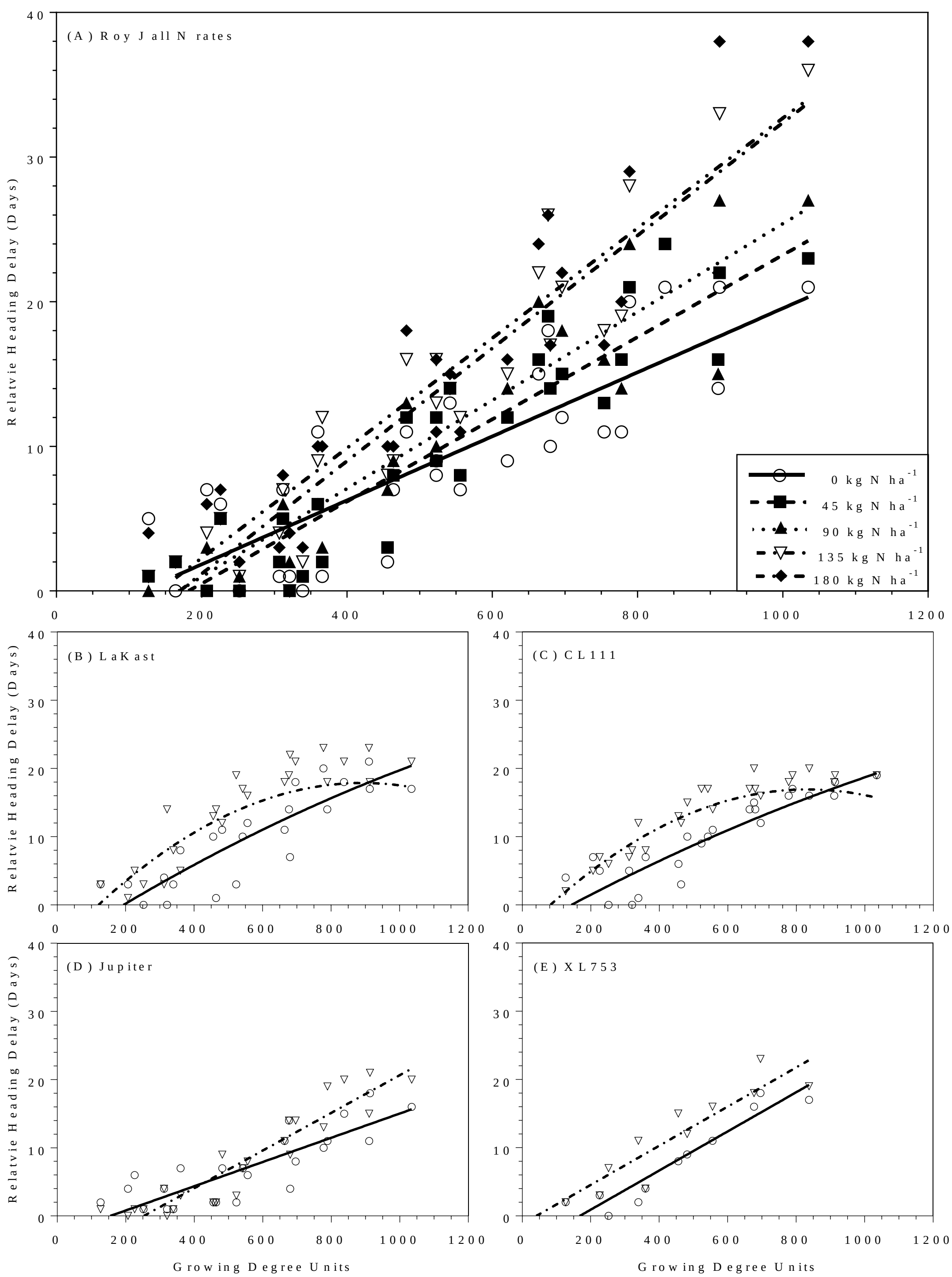


Fig. 2.4. Relative grain yield of five rice cultivars (Roy J, LaKast, CL111, Jupiter, XL753) receiving five different N rates regressed across cumulative growing degree units at the time of N fertilization for A) three site-years at the Pine Tree Research Station (PTRS) and B) two site-years at the Rice Research and Extension Center (RREC) in 2015 and 2016. Regression coefficients are listed in Table 2.9.

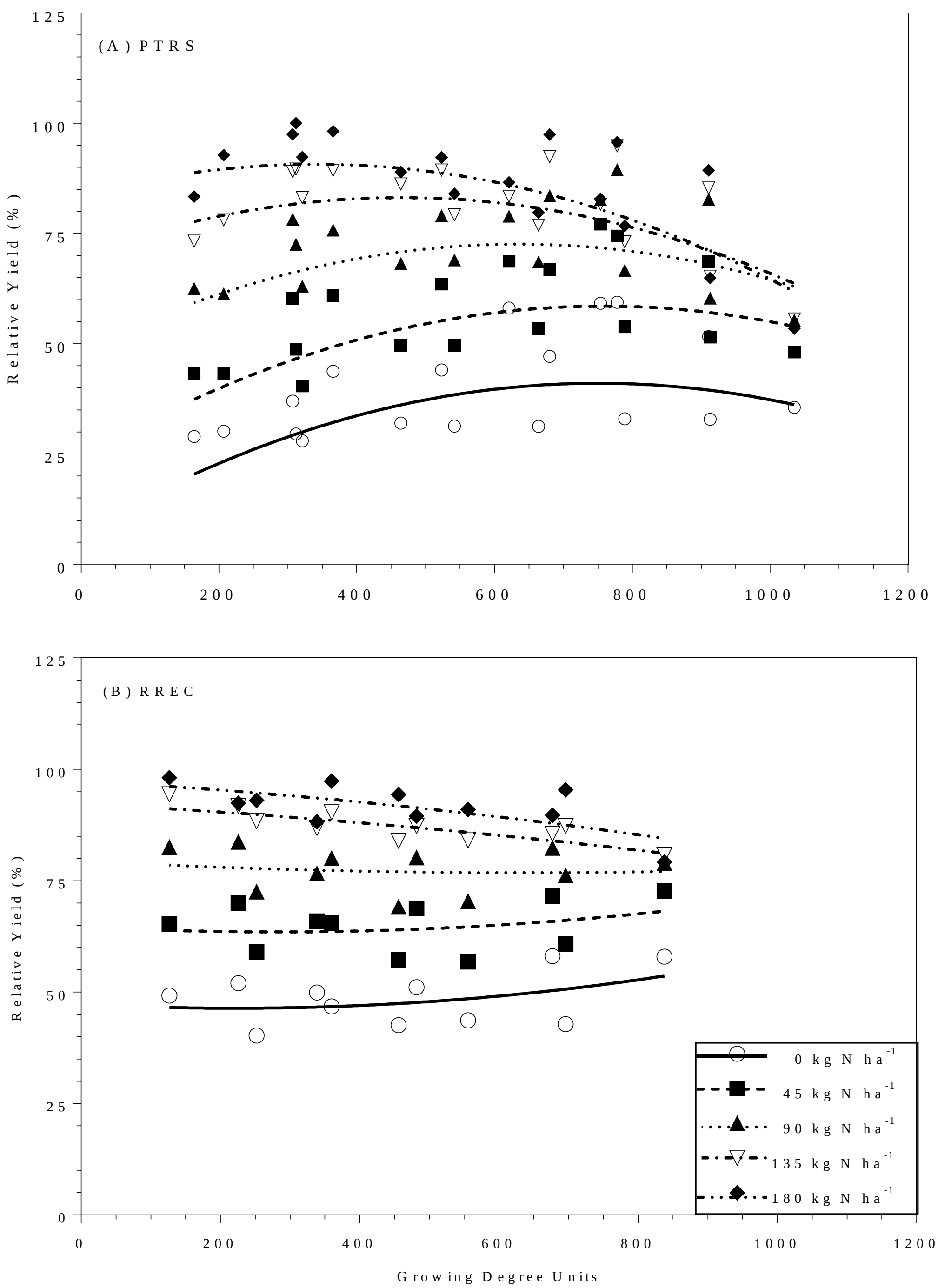


Fig. 2.5. Yield components including (A) tillers plant^{-1}, (B) panicles m^{-2}, (C) effective tillers, (D) spikelets panicle^{-1}, (E) percent filled spikelets, and (F) rough rice seed weight for Roy J regressed across cumulative growing degree units at the time of fertilization for two site-years at the Pine Tree Research Station in 2015 and 2016 (PTRS-2015a and PTRS-2016). Regression coefficients are listed in Table 2.11.

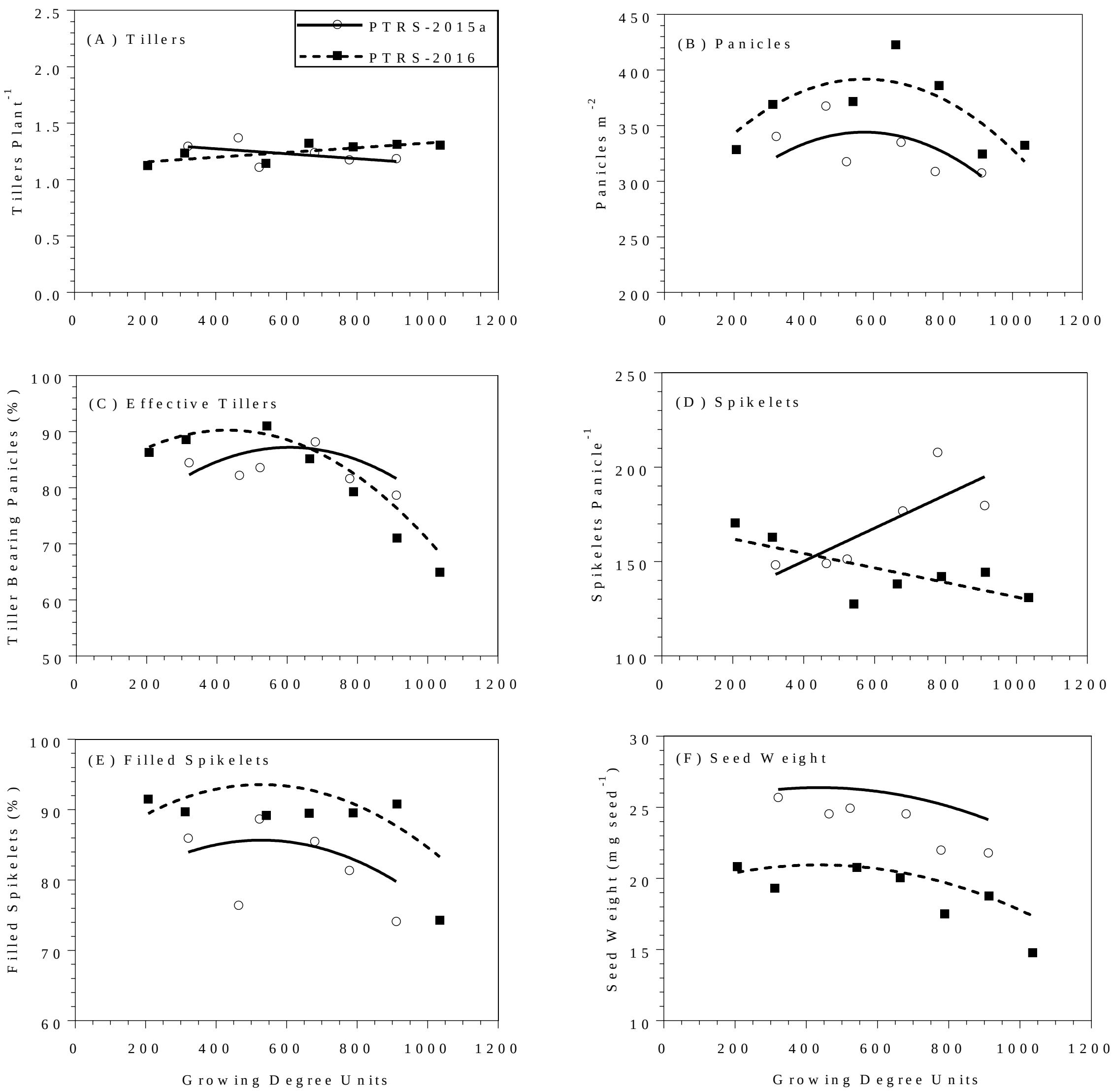
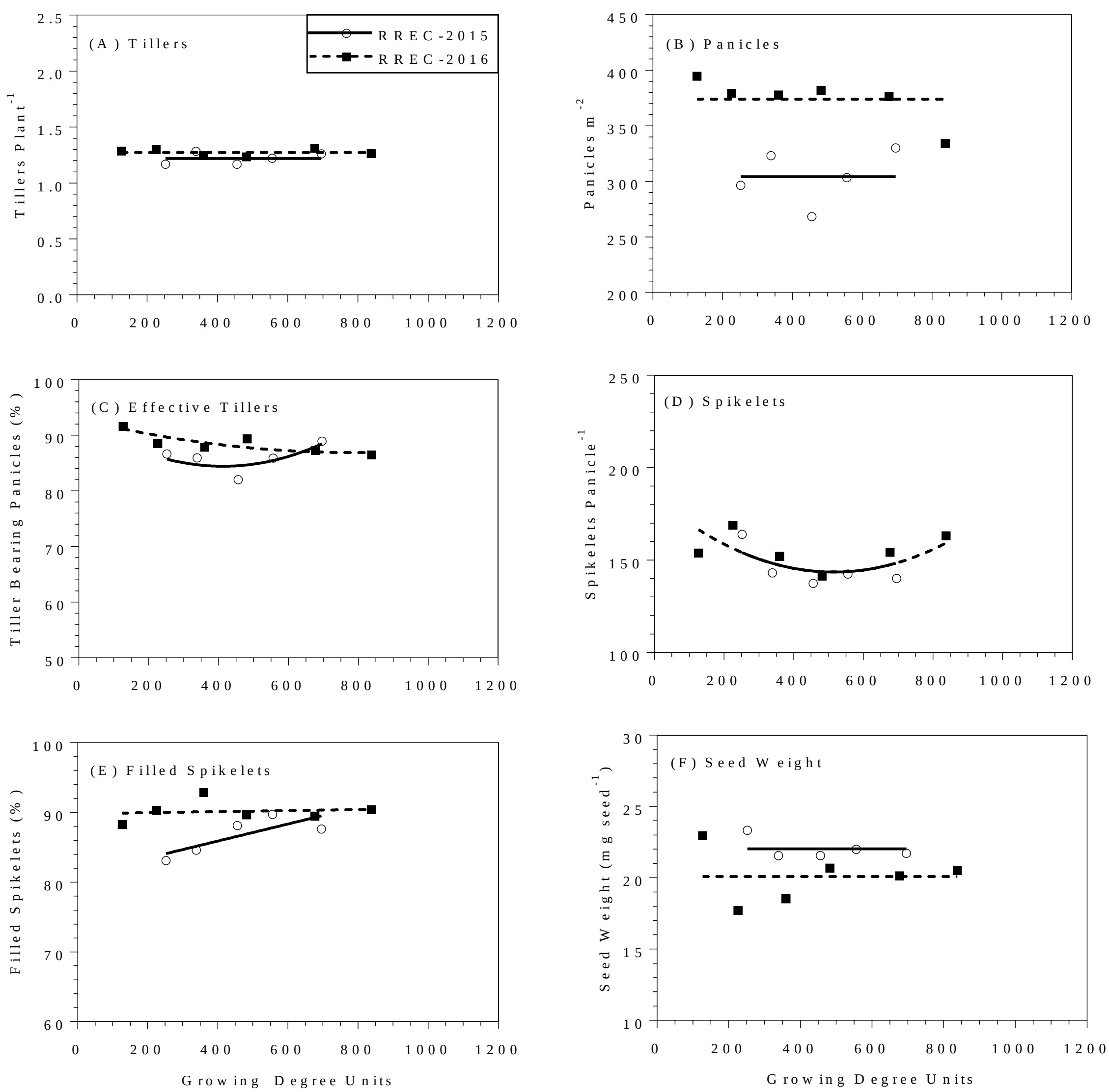


Fig. 2.6. Yield components including A) tillers plant^{-1}, (B) panicles m^{-2}, (C) effective tillers, (D) spikelets panicle^{-1}, (E) percent filled spikelets, and (F) rough rice seed weight for Roy J regressed across cumulative growing degree units at the time of fertilization for two site-years at the Rice Research and Extension Center in 2015 and 2016 (RREC-2015 and RREC-2016). Regression coefficients are listed in Table 2.11.



Appendices

Appendix 2.1. Selected dates of herbicide application timings at five site-years at the Pine Tree Research Station (PTRS) and Rice Research and Extension Center (RREC) in 2015 and 2016.

Site-year	Application date	Fertilization times treated†	Herbicides applied ‡			Herbicide rates		
						------------kg a.i. ha^{-1}------------		
PTRS-2015a	10 Apr	1, 2, 3, 4, 5, 6	A	--§	--	0.3159	--	--
	8 May	1, 2, 3, 4, 5, 6	B	+ C	--	2.2464	+ 0.3685	--
	23 June	5, 6	D	+ E	--	3.3695	+ 0.0004	--
PTRS-2015b	5 May	1, 2, 3, 4, 5, 6	A	+ C	--	0.2106	+ 0.2896	--
	27 May	1	B	+ D	+ E	2.1060	+ 3.3695	+ 0.0004
	4 June	2, 3, 4, 5, 6	B	+ D	+ E	2.1060	+ 3.3695	+ 0.0004
PTRS-2016	7 Apr	1, 2, 3, 4, 5, 6, 7	A	+ C	--	0.1579	+ 0.3243	--
	10 May	1, 2, 3, 4, 5, 6, 7	B	+ E	--	2.2464	+ 0.0004	--
	9 June	3, 4, 5, 6, 7	B	+ C	+ D	2.2464	+ 0.2896	+ 3.3695
	30 June	6, 7	F	--	--	0.1221	--	--
RREC-2015	1 May	1, 2, 3, 4, 5	G	--	--	0.4387	--	--
	27 May	1	C	+ E	+ F	0.3159	+ 0.0004	+ 0.1221
	1 June	2, 3, 4, 5	E	+ H	--	0.0004	+ 0.9266	--
RREC-2016	27 Apr	1, 2, 3, 4, 5, 6	A	+ C	--	0.2106	+ 0.2632	--
	19 May	1, 2, 3, 4, 5, 6	C	+ E	--	0.3159	+ 0.0006	--

† Fertilization times are identified in chronological order as times 1, 2, 3, 4, 5, 6, and 7 for each site and are defined in Table 2.2.

‡ Herbicide A, (Clomazone [2-(2-chlorophenyl)methyl-4, 4-dimethyl-3-isoxazolidinone] Command® 3ME); Herbicide B, (Thiobencarb {S-[(4-chlorophenyl)methyl] dimethylcarbamothioate} Bolero® 8 EC); Herbicide C, (Quinclorac (3,7-dichloro-8-quinolinecarboxylic acid) Facet® L; Herbicide D, (Propanil [3,4-dichloropropionanilide] RiceShot®); Herbicide E, (Halosulfuron + Thifensulfuron [Halosulfuron-methyl + Thifensulfuron-methyl] Permit® Plus); Herbicide F, (Fenoxaprop-p-ethyl {(+)-ethyl 2-[4-[(6-chloro-2-benzoxazolyl) oxy] phenoxy]propanoate} RiceStar® HT); Herbicide G, (Clomazone + Quinclorac [2-(2-chlorophenyl)methyl-4, 4-dimethyl-3-isoxazolidinone + 3,7-dichloro-8-quinolinecarboxylic acid] Obey™); Herbicide H, (Pendimethalin [N-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine] Prowl 3.3 EC).

§ Herbicide was not applied.

Appendix 2.2. Analysis of covariance p-values for 50% heading delay by cultivar as affected by five N rates (NR) regressed across cumulative fertilization days delayed (FD) at the time of fertilizer application as defined by the final model for four trials conducted at the Pine Tree Research Station (PTRS) and the Rice Research and Extension Center (RREC) in 2015 and 2016.

Site-year	Source of variation	df†	CL111	Jupiter	LaKast	Roy J	XL753
			Heading delay				
			---------------------------*P* value-------------------------				
PTRS-2015a	NR	4	0.3050	0.9784	0.5079	0.7571	--§
	FD	1	0.0001	NS	NS	NS	--
	FD × NR	4	NS‡	0.0418	<0.0001	<0.0001	--
	FD × FD	1	0.1469	0.0007	NS	<0.0001	--
	FD × FD × NR	4	NS	NS	NS	NS	--
PTRS-2016	NR	4	0.9981	0.9905	0.0001	0.2285	--
	FD	1	NS	NS	<0.0001	<0.0001	--
	FD × NR	4	<0.0001	0.0264	NS	NS	--
	FD × FD	1	NS	0.0135	NS	NS	--
	FD × FD × NR	4	0.0546	NS	NS	<0.0001	--
RREC-2015	NR	4	0.4662	0.9581	0.8964	0.9805	0.6904
	FD	1	<0.0001	NS	<0.0001	NS	NS
	FD × NR	4	NS	0.0901	NS	0.0035	0.0006
	FD × FD	1	0.0831	0.0004	NS	<0.0001	0.0002
	FD × FD × NR	4	NS	NS	NS	NS	NS
RREC-2016	NR	4	0.8711	0.3725	0.6861	0.6419	0.2714
	FD	1	NS	NS	0.0157	NS	0.0042
	FD × NR	4	<0.0001	0.0796	NS	<0.0001	NS
	FD × FD	1	NS	0.0003	0.0879	<0.0001	0.0618
	FD × FD × NR	4	NS	NS	NS	NS	NS

† The df for the final model is the sum of the df for each model term (intercept, linear, and quadratic) listed as a source of variation.
‡ NS, not significant (*P*>0.15) in the final model.
§ 50% heading measurement not taken.

Appendix 2.3. Regression coefficients for 50% heading delay by cultivar as affected by N rate regressed across fertilizer application time expressed as days fertilization was delayed as defined by the final model at the Pine Tree Research Station (PTRS) in 2015 and 2016.

		Parameter estimates†					
		PTRS-2015a			PTRS-2016		
Cultivar	N rate	Intercept	Linear	Quadratic	Intercept	Linear	Quadratic
	kg N ha^{-1}	Coefficients					
CL111	0	0.417§	0.583	-0.0046§	-1.431§	0.120§	0.0026§
	45	-0.750§	0.583	-0.0046§	-0.564§	0.613	-0.0047
	90	-0.416§	0.583	-0.0046§	-0.970§	0.235	0.0010§
	135	-2.250§	0.583	-0.0046§	-1.257§	0.555	-0.0049
	180	-2.416§	0.583	-0.0046§	-0.730§	0.413	-0.0028§
	SE	1.485	0.583	0.0031	1.626	0.130	0.0023
	R^2		0.56			0.79	
Jupiter	0	-0.305§	0.013§	0.0069	-0.645§	0.077§	0.0032
	45	-0.044§	0.008§	0.0069	-0.925§	0.122§	0.0032
	90	-0.896§	0.099§	0.0069	-0.515§	0.172	0.0032
	135	-0.300§	0.159	0.0069	0.220§	0.225	0.0032
	180	0.055§	0.190	0.0069	-0.491§	0.239	0.0032
	SE	1.187	0.082	0.0017	1.678	0.080	0.0012
	R^2		0.62			0.49	
LaKast	0	-3.981§	0.617	NS‡	-2.913§	0.340	NS
	45	-2.733§	0.540	NS	-0.342§	0.340	NS
	90	-0.018§	0.432	NS	-0.199§	0.340	NS
	135	-0.543§	0.279	NS	1.944	0.340	NS
	180	1.395§	0.298	NS	-1.771	0.340	NS
	SE	2.336	0.097	--	0.943	0.018	--
	R^2		0.85			0.93	
Roy J	0	-0.644§	0.635	-0.0083	-2.551	0.388	-0.0014§
	45	-0.036§	0.751	-0.0083	1.311§	0.388	0.0006§
	90	0.075§	0.657	-0.0083	-0.148§	0.388	0.0016§
	135	1.102§	0.850	-0.0083	-1.410§	0.388	0.0042
	180	-0.452§	0.788	-0.0083	-2.164§	0.388	0.0048
	SE	1.043	0.072	0.0015	1.435	0.069	0.0014
	R^2		0.91			0.79	

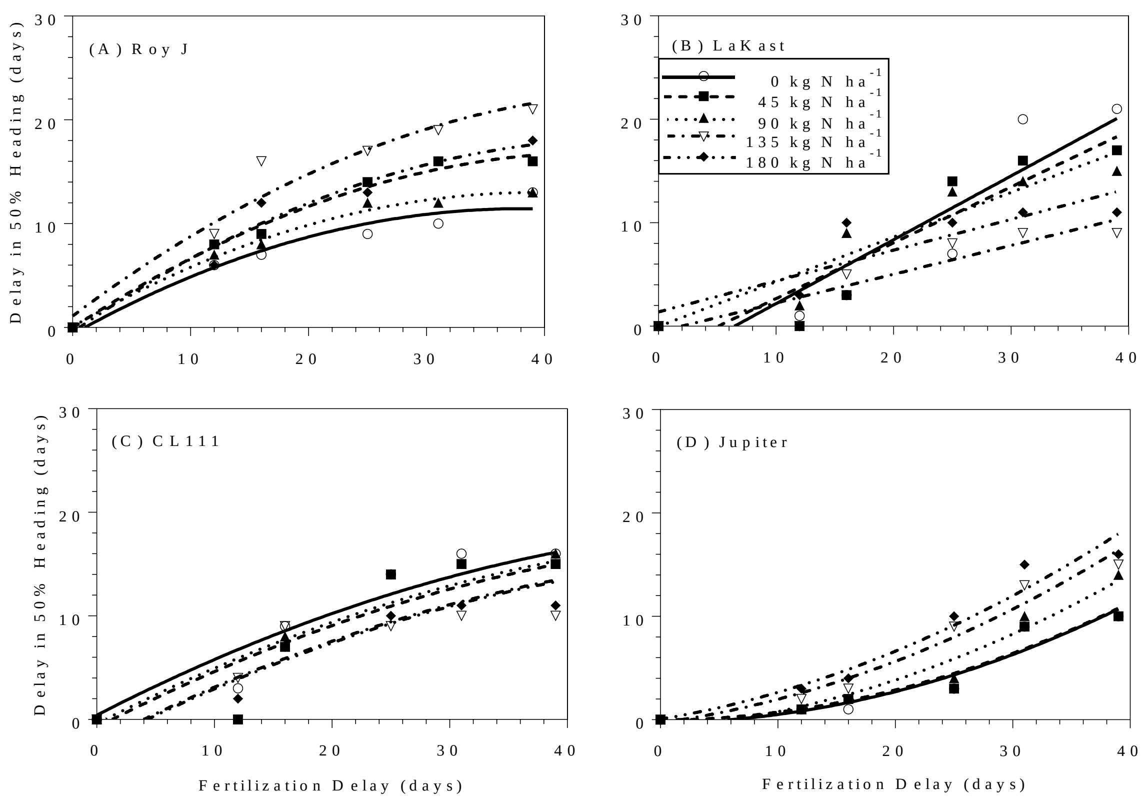
† Linear ($y = a + bx$) and quadratic ($y = a + bx + cx^2$) models where y = 50% heading delay (days), x = fertilizer application delay (days accumulated), a = intercept coefficient, b = linear slope coefficient, and c = quadratic slope coefficient.
‡ NS, not significant (P>0.15) in the final model.
§ Coefficient is not significantly different than 0 (P>0.10).

Appendix 2.4. Regression coefficients for 50% heading delay by cultivar as affected by N rate regressed across fertilizer application time expressed as days fertilization was delayed as defined by the final model at the Rice Research and Extension Center (RREC) in 2015 and 2016.

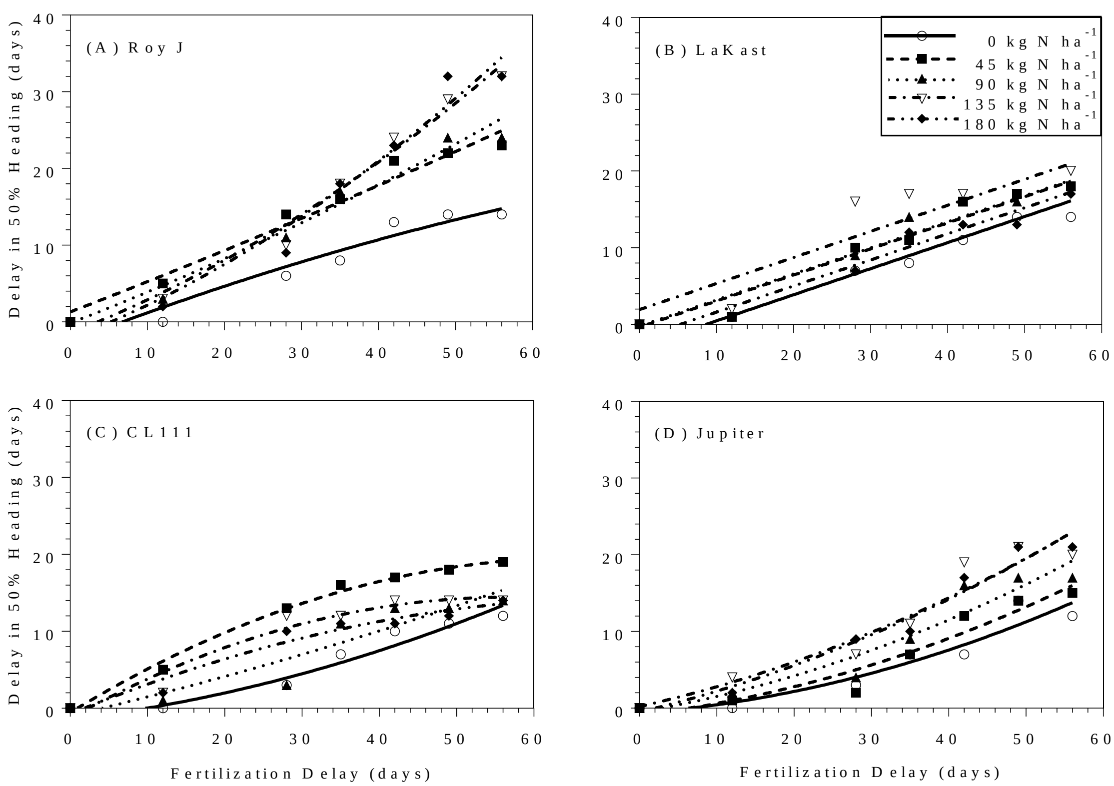
		Parameter estimates†					
		RREC-2015			RREC-2016		
Cultivar	N rate	Intercept	Linear	Quadratic	Intercept	Linear	Quadratic
	kg N ha^{-1}	Coefficients					
CL111	0	0.253§	0.541	-0.0067	-1.303§	0.280	NS
	45	0.253§	0.541	-0.0067	0.081§	0.408	NS
	90	0.053§	0.541	-0.0067	-0.349§	0.384	NS
	135	0.453§	0.541	-0.0067	0.050§	0.409	NS
	180	-1.147§	0.541	-0.0067	-1.204§	0.399	NS
	SE	0.859	0.104	0.0036	1.212	0.041	--
	R^2		0.65			0.95	
Jupiter	0	0.508§	-0.240	0.0182	1.723§	-0.001§	0.0056
	45	0.589§	-0.274	0.0182	-0.082§	0.074§	0.0056
	90	-0.070§	-0.047§	0.0182	-1.274§	0.109§	0.0056
	135	-0.646§	-0.049§	0.0182	-1.387§	0.148	0.0056
	180	-0.061§	-0.020§	0.0182	-0.636§	0.151	0.0056
	SE	1.331	0.131	0.0034	1.256	0.073	0.0013
	R^2		0.71			0.65	
LaKast	0	-0.548§	0.635	NS‡	-1.031§	0.242	0.0033
	45	0.052§	0.635	NS	0.636§	0.242	0.0033
	90	-0.148§	0.635	NS	0.303§	0.242	0.0033
	135	0.052§	0.635	NS	-0.864§	0.242	0.0033
	180	0.252§	0.635	NS	-0.031§	0.242	0.0033
	SE	0.703	0.027	--	1.301	0.093	0.0018
	R^2		0.97			0.35	
Roy J	0	0.293§	-0.258	0.0250	1.084§	-0.040§	0.0080
	45	0.259§	-0.172	0.0250	0.831§	0.101§	0.0080
	90	-0.234§	-0.096§	0.0250	-0.189§	0.239	0.0080
	135	-0.167§	0.024§	0.0250	-0.231§	0.302	0.0080
	180	-0.112§	0.006§	0.0250	-1.200§	0.301	0.0080
	SE	0.815	0.080	0.0024	1.216	0.071	0.0012
	R^2		0.91			0.85	
XL753	0	-0.483§	0.343	0.0110	-2.156	0.249	0.0030
	45	-0.454§	0.438	0.0110	-0.156§	0.249	0.0030
	90	-0.563§	0.279	0.0110	-0.989§	0.249	0.0030
	135	0.696§	0.234	0.0110	-0.989§	0.249	0.0030
	180	-0.245§	0.229	0.0110	0.344§	0.249	0.0030
	SE	0.716	0.071	0.0021	1.098	0.078	0.0016
	R^2		0.84			0.46	

† Linear ($y = a + bx$) and quadratic ($y = a + bx + cx^2$) models where y = 50% heading delay (days), x = fertilizer application delay (days accumulated), a = intercept coefficient, b = linear slope coefficient, and c = quadratic slope coefficient.
‡ NS, not significant (P>0.15) in the final model.
§ Coefficient is not significantly different than 0 (P>0.10).

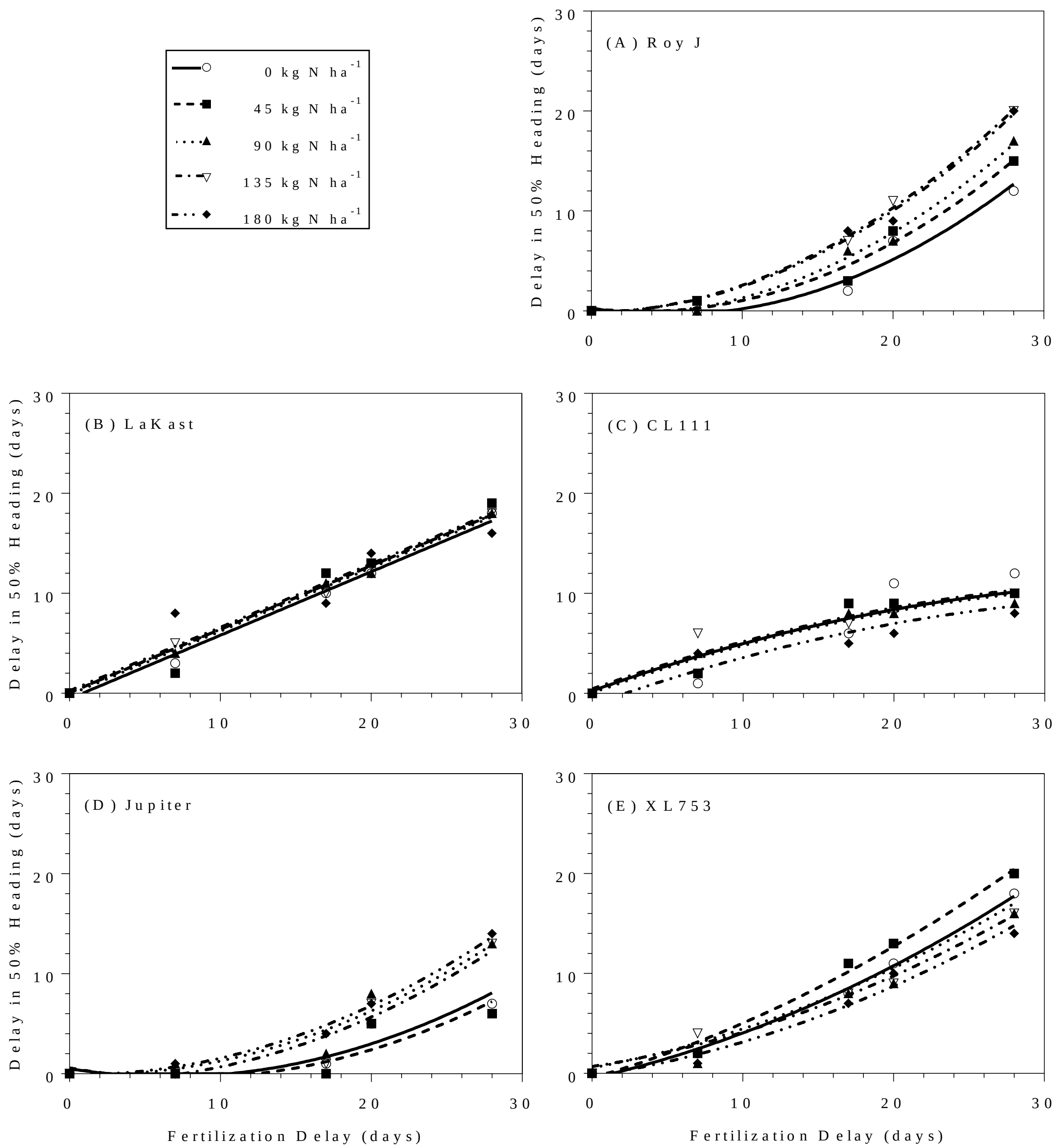
Appendix 2.5. The delay in 50% heading for four rice cultivars [(A) Roy J, (B) LaKast, (C) CL111, (D) Jupiter] receiving five different N rates regressed across fertilizer application time expressed as days fertilization was delayed at the Pine Tree Research Station (PTRS) PTRS-2015a. Regression coefficients are listed in Appendix 2.3.



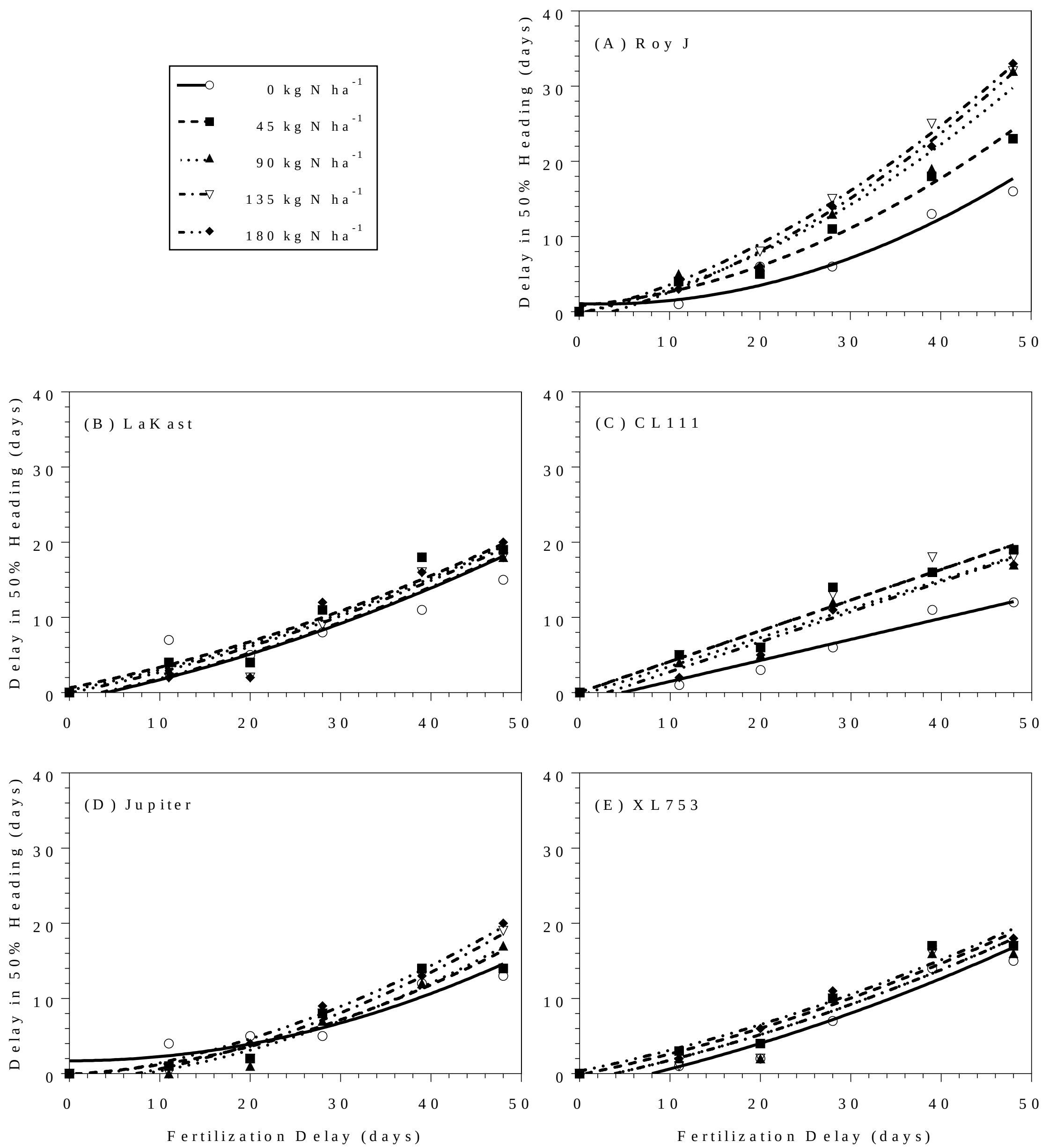
Appendix 2.6. The delay in 50% heading for four rice cultivars [(A) Roy J, (B) LaKast, (C) CL111, (D) Jupiter] receiving five different N rates regressed across fertilizer application time expressed as days fertilization was delayed at the Pine Tree Research Station (PTRS) PTRS-2016. Regression coefficients are listed in Appendix 2.3.



Appendix 2.7. The delay in 50% heading for five rice cultivars [(A) Roy J, (B) LaKast, (C) CL111, (D) Jupiter, (E) XL753] receiving five different N regressed across fertilizer application time expressed as days fertilization was delayed at the Rice Research and Extension Center (RREC) RREC-2015. Regression coefficients are listed in Appendix 2.4.



Appendix 2.8. The delay in 50% heading for five rice cultivars [(A) Roy J, (B) LaKast, (C) CL111, (D) Jupiter, (E) XL753] receiving five different N regressed across fertilizer application time expressed as days fertilization was delayed at the Rice Research and Extension Center (RREC) RREC-2016. Regression coefficients are listed in Appendix 2.4.



Appendix 2.9. Analysis of covariance p-values for grain yield by cultivar as affected by five N rates (NR) regressed across cumulative growing degree units (GDU) at fertilizer application time as defined by the final model for three site-years at the Pine Tree Research Station (PTRS) and two site-years at the Rice Research and Extension Center (RREC) in 2015 and 2016.

			Cultivar				
Site-year	Source of variation	df†	CL111	Jupiter	LaKast	Roy J	XL753
			---------------------------*P* value---------------------------				
PTRS-2015a	NR	4	<0.0001	<0.0001	<0.0001	<0.0001	--‡
	GDU	1	NS§	NS	NS	NS	--
	GDU × NR	4	<0.0001	<0.0001	<0.0001	<0.0001	--
	GDU × GDU	1	NS	0.0171	NS	<0.0001	--
	GDU × GDU × NR	4	<0.0001	NS	0.0025	NS	--
PTRS-2015b	NR	4	--	--	--	0.0007	<0.0001
	GDU	1	--	--	--	NS	NS
	GDU × NR	4	--	--	--	<0.0001	<0.0001
	GDU × GDU	1	--	--	--	NS	NS
	GDU × GDU × NR	4	--	--	--	<0.0001	<0.0001
PTRS-2016	NR	4	<0.0001	<0.0001	<0.0001	<0.0001	--
	GDU	1	NS	0.0003	NS	NS	--
	GDU × NR	4	<0.0001	NS	0.0026	0.0001	--
	GDU × GDU	1	0.0004	NS	NS	NS	--
	GDU × GDU × NR	4	NS	<0.0001	<0.0001	<0.0001	--
RREC-2015	NR	4	<0.0001	0.0002	<0.0001	<0.0001	<0.0001
	GDU	1	NS	NS	0.0010	<0.0001	0.0015
	GDU × NR	4	NS	<0.0001	NS	NS	NS
	GDU × GDU	1	NS	NS	0.0013	<0.0001	NS
	GDU × GDU × NR	4	NS	<0.0001	NS	NS	NS
RREC-2016	NR	4	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	GDU	1	NS	NS	0.0132	NS	NS
	GDU × NR	4	<0.0001	<0.0001	NS	0.0022	0.0007
	GDU × GDU	1	NS	NS	NS	NS	NS
	GDU × GDU × NR	4	NS	<0.0001	<0.0001	NS	0.0152

† The df for the final model is the sum of the df for each model term (intercept, linear, and quadratic) listed as a source of variation.
‡ Cultivar not included at the location.
§ NS, not significant (*P*>0.15) in the final model.

Appendix 2.10. Regression coefficients for grain yield by cultivar as affected by N rate regressed across cumulative growing degree unit at fertilization time as defined by the final model for three trials at the Pine Tree Research Station (PTRS) in 2015 and 2016.

		Parameter estimates†											
		PTRS-2015a				PTRS-2015b				PTRS-2016			
Cultivar	N rate	Intercept	Linear	Quadratic	R^2	Intercept	Linear	Quadratic	R^2	Intercept	Linear	Quadratic	R^2
	kg N ha^{-1}	Coefficients											
CL111	0	-905‡	11.84	-0.0061		--§	--	--		1932	4.118	-0.0026	
	45	-509‡	14.70	-0.0085		--	--	--		3434	4.083	-0.0026	
	90	925	16.76	-0.0111		--	--	--		5710	2.403	-0.0026	
	135	3687	13.87	-0.0118		--	--	--		7396	0.880‡	-0.0026	
	180	9407	-3.84‡	0.0021‡		--	--	--		8300	-0.400‡	-0.0026	
	SE	1254	4.304	0.0034	0.59	--	--	--	--	355	0.959	0.00071	0.81
Jupiter	0	-1690	13.47	-0.0058		--	--	--		2155	3.79	-0.0023	
	45	-325‡	14.49	-0.0058		--	--	--		4208	3.79	-0.0022	
	90	1181	15.00	-0.0058		--	--	--		6246	3.79	-0.0025	
	135	4417	11.81	-0.0058		--	--	--		8266	3.79	-0.0042	
	180	5285	11.57	-0.0058		--	--	--		9752	3.79	-0.0057	
	SE	993	3.037	0.0023	0.56	--	--	--	--	334	1.006	0.00088	0.89
LaKast	0	-582‡	11.76	-0.0058		--	--	--		3313	-1.014	0.0013‡	
	45	-1346‡	18.62	-0.0107		--	--	--		4124	3.723	-0.0020	
	90	3089	9.19	-0.0041‡		--	--	--		5731	6.822	-0.0062	
	135	5016	10.63	-0.0080		--	--	--		8174	4.485	-0.0065	
	180	9001	-2.06‡	0.0022‡		--	--	--		10609	-0.151‡	-0.0042	
	SE	1247	4.369	0.0036	0.53	--	--	--	--	557	2.146	0.00169	0.57
Roy J	0	-2879	22.50	-0.016		1395	6.32	-0.00070‡		3156	-2.37‡	0.0020‡	
	45	-1161‡	22.46	-0.016		3210	5.43‡	0.00278‡		2809	5.87	-0.0053	
	90	1954	19.88	-0.016		4375	9.20	-0.00422‡		4554	9.48	-0.0106	
	135	4147	17.59	-0.016		4912	15.24	-0.01428		6444	8.48	-0.0112	
	180	4505	17.29	-0.016		6053	15.49	-0.01713		7915	9.76	-0.0145	
	SE	902	2.695	0.0020	0.75	747	3.71	0.00379	0.53	551	2.14	0.00177	0.72
XL753	0	--	--	--		3345	4.84‡	0.00069‡		--	--	--	
	45	--	--	--		2782	21.39	-0.02118		--	--	--	
	90	--	--	--		6872	12.78	-0.01401		--	--	--	
	135	--	--	--		7205	16.97	-0.01924		--	--	--	
	180	--	--	--		9441	10.91	-0.01450		--	--	--	
	SE	--	--	--	--	1030	4.81	0.00536	0.55	--	--	--	--

† Regression models evaluated included quadratic ($y = a + bx + cx^2$) models where y = grain yield (kg ha^{-1}), x = fertilizer application time (DD10’s accumulated), a = intercept coefficient, b = linear slope coefficient, and c = quadratic slope coefficient.

‡ Coefficient is not different than 0 (P>0.10).

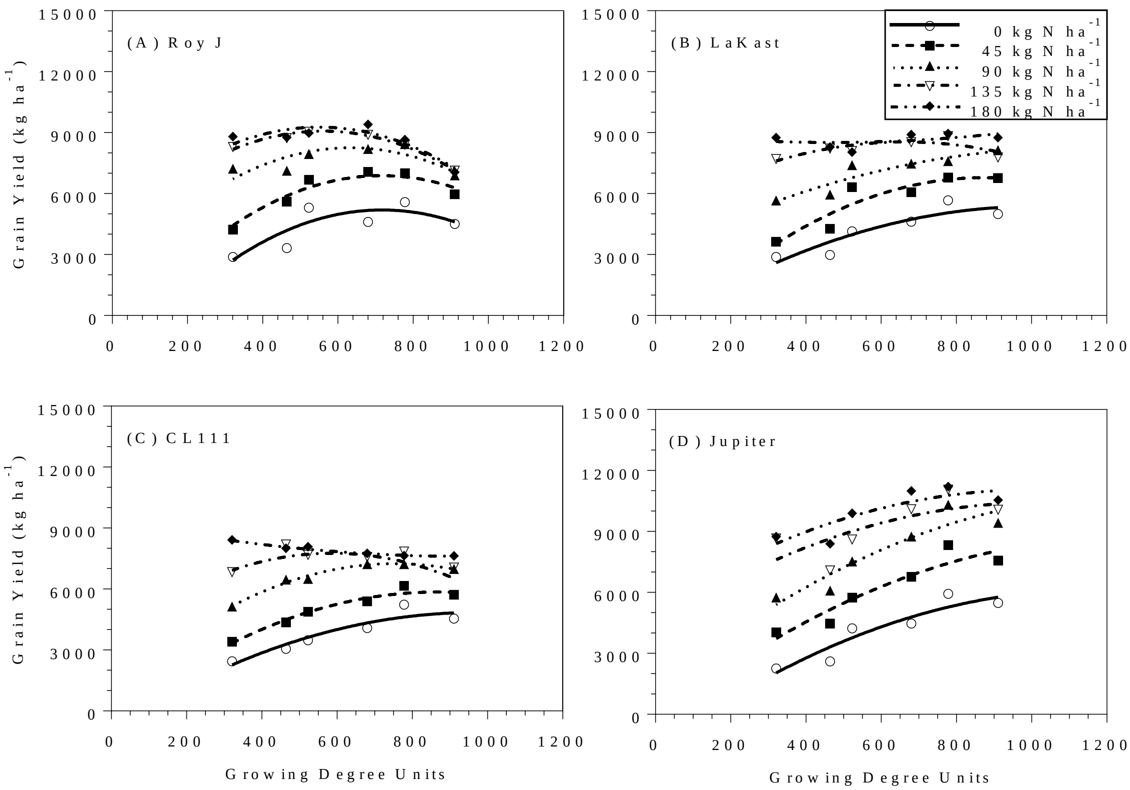
§ Cultivar not included at this site.

Appendix 2.11. Regression coefficients for grain yield by cultivar as affected by N rate regressed across cumulative growing degree units at fertilizer application time as defined by the final model for two site-years at the Rice Research and Extension Center (RREC) in 2015 and 2016.

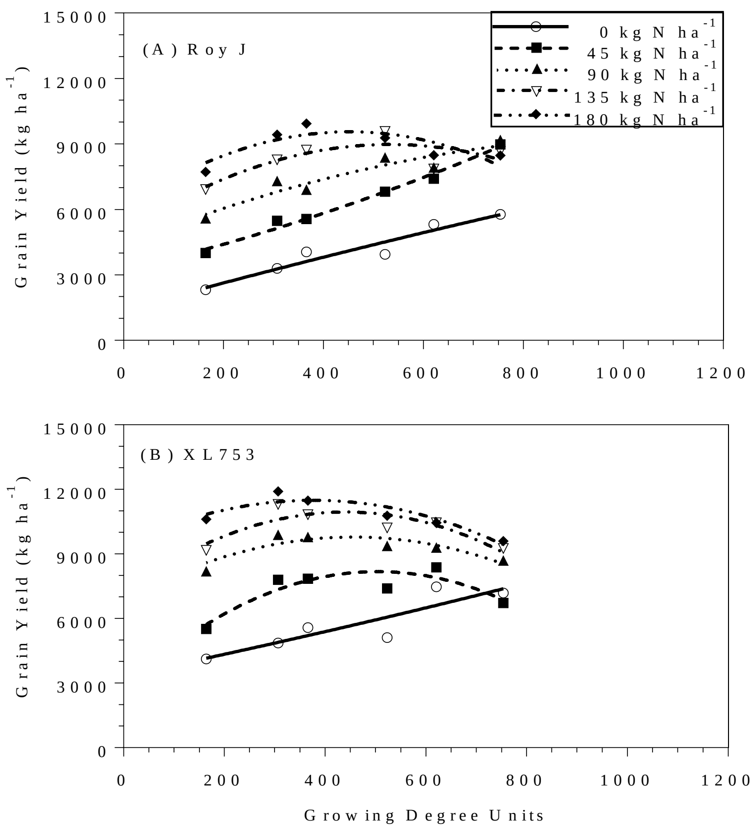
		Parameter estimates†					
		RREC-2015			RREC-2016		
Cultivar	N rate	Intercept	Linear	Quadratic	Intercept	Linear	Quadratic
	kg N ha^{-1}	Coefficients					
CL111	0	3446	NS‡	NS	4631	2.808	NS
	45	4551	NS	NS	6168	2.652	NS
	90	5743	NS	NS	7788	0.098§	NS
	135	5873	NS	NS	9538	-2.870	NS
	180	6707	NS	NS	10182	-4.476	NS
	SE	203	--	--	230	0.435	--
	R^2		0.79			0.85	
Jupiter	0	4676	-2.78§	0.0039§	6329	-8.64	0.00906
	45	7848	-11.60§	0.0138§	7902	-7.62	0.00633
	90	13283	-34.21	0.0383	9289	-6.73	0.00596
	135	14947	-32.77	0.0362	11256	-10.88	0.00867
	180	16725	-39.66	0.0437	9734	-0.66§	-0.00062§
	SE	2007	9.14	0.0096	500	2.43	0.00245
	R^2		0.58			0.59	
LaKast	0	5836	-9.46	0.0097	4614	2.54	-0.0014§
	45	7535	-9.46	0.0097	6565	2.54	-0.0016§
	90	9238	-9.46	0.0097	7919	2.54	-0.0028
	135	10493	-9.46	0.0097	9519	2.54	-0.0056
	180	11008	-9.46	0.0097	9534	2.54	-0.0063
	SE	624	2.78	0.0029	265	1.003	0.00110
	R^2		0.92			0.87	
Roy J	0	2563	11.70	-0.012	3260	0.173§	NS
	45	4193	11.70	-0.012	5271	-0.257§	NS
	90	5249	11.70	-0.012	7600	-1.637	NS
	135	6720	11.70	-0.012	7989	-0.506§	NS
	180	7020	11.70	-0.012	8695	-1.081	NS
	SE	588	2.53	0.0026	242	0.473	--
	R^2		0.89			0.78	
XL753	0	5840	-1.78	NS	6198	2.2069§	0.00140§
	45	8175	-1.78	NS	6955	9.0035	-0.00580
	90	9846	-1.78	NS	10196	1.5317§	-0.00064§
	135	11546	-1.78	NS	10939	1.8827§	-0.00185§
	180	12591	-1.78	NS	11180	4.8032	-0.00589
	SE	371	0.54	--	493	2.307	0.00230
	R^2		0.88			0.59	

†Regression models evaluated included linear ($y = a + bx$) and quadratic ($y = a + bx + cx^2$) models where y = grain yield (kg ha^{-1}), x = fertilizer application time (DD10's accumulated), a = intercept coefficient, b = linear slope coefficient, and c = quadratic slope coefficient.
‡ NS, not significant (P>0.15) in the final model.
§ Coefficient is not different than 0 (P>0.10).

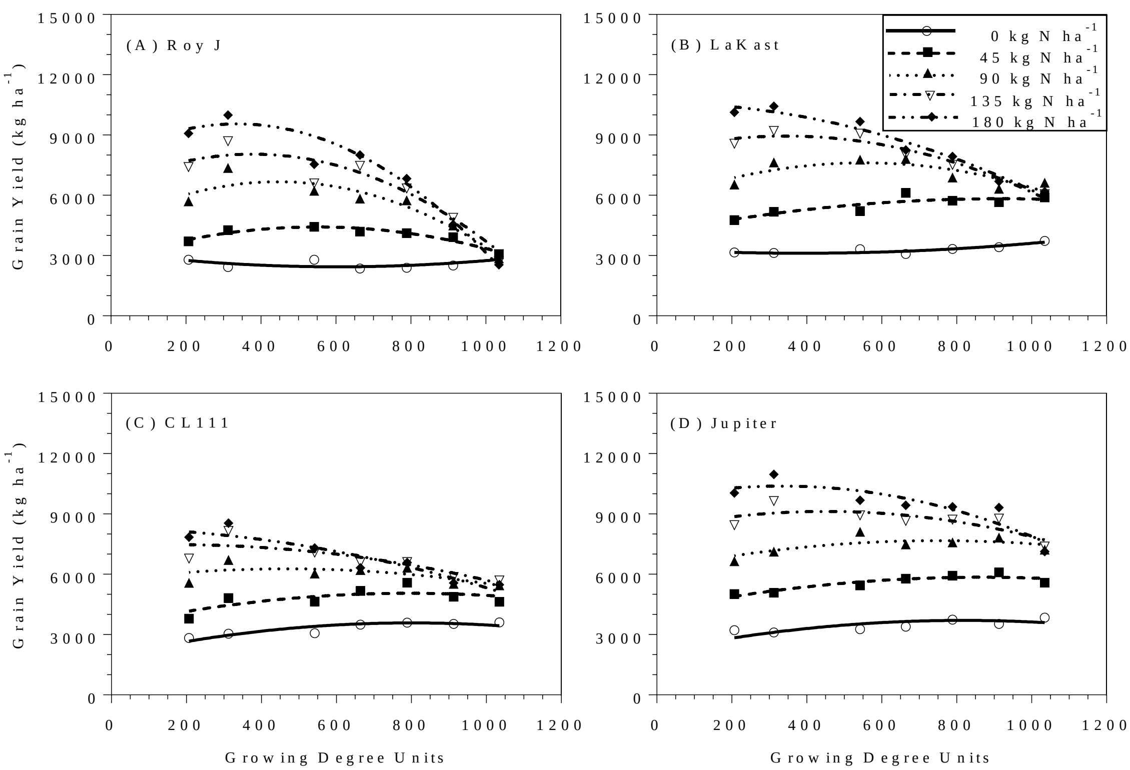
Appendix 2.12. Grain yield for four rice cultivars [(A) Roy J, (B) LaKast, (C) CL111, (D) Jupiter] receiving five different N rates regressed across growing degree units accumulated at the time of fertilization at the Pine Tree Research Station (PTRS-2015a). Regression coefficients are listed in Appendix 2.10.



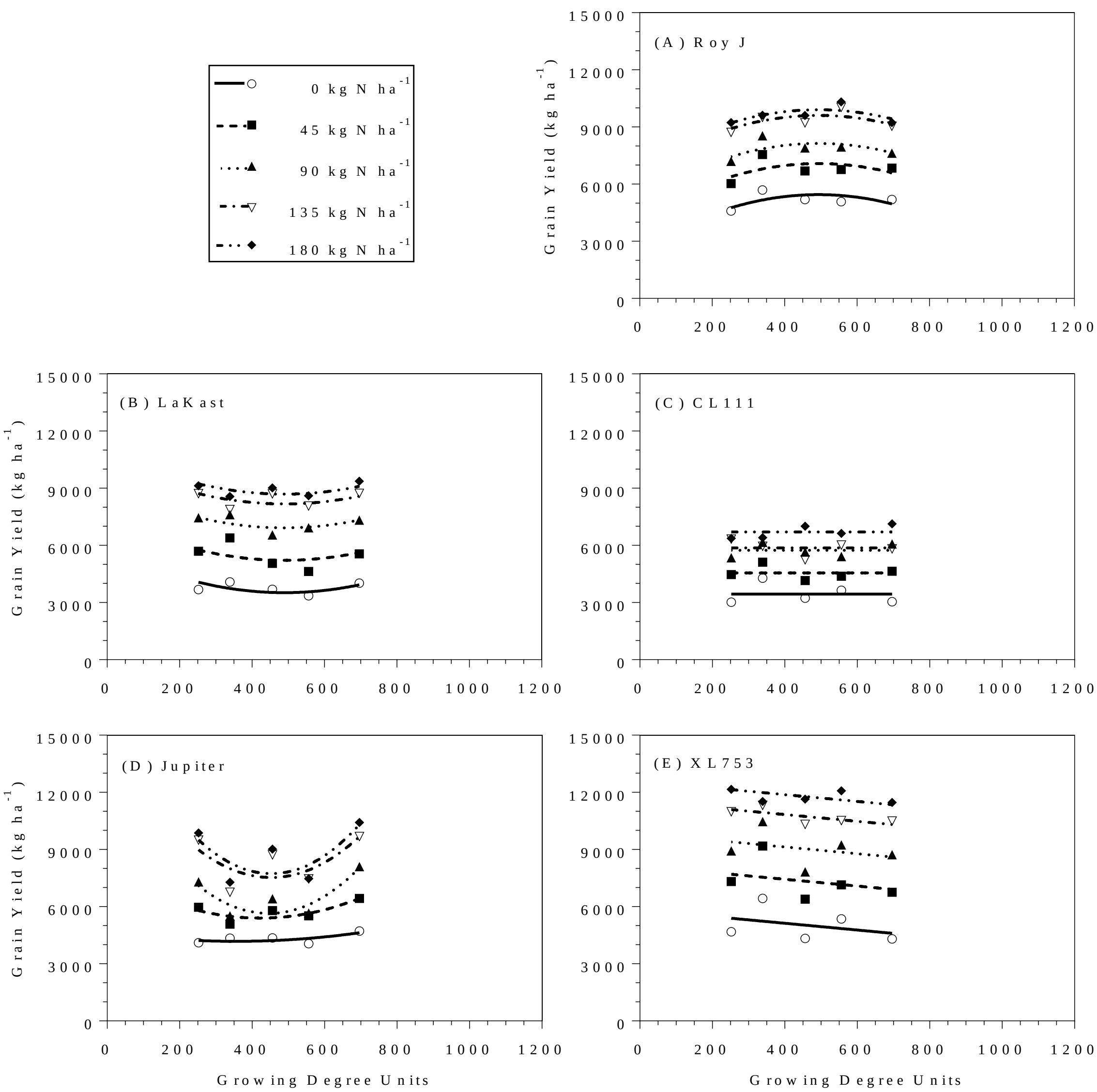
Appendix 2.13. Grain yield for two rice cultivars [(A) Roy J, (B) XL753] receiving five different N rates regressed across growing degree units accumulated at the time of fertilization at the Pine Tree Research Station (PTRS-2015b). Regression coefficients are listed in Appendix 2.10.



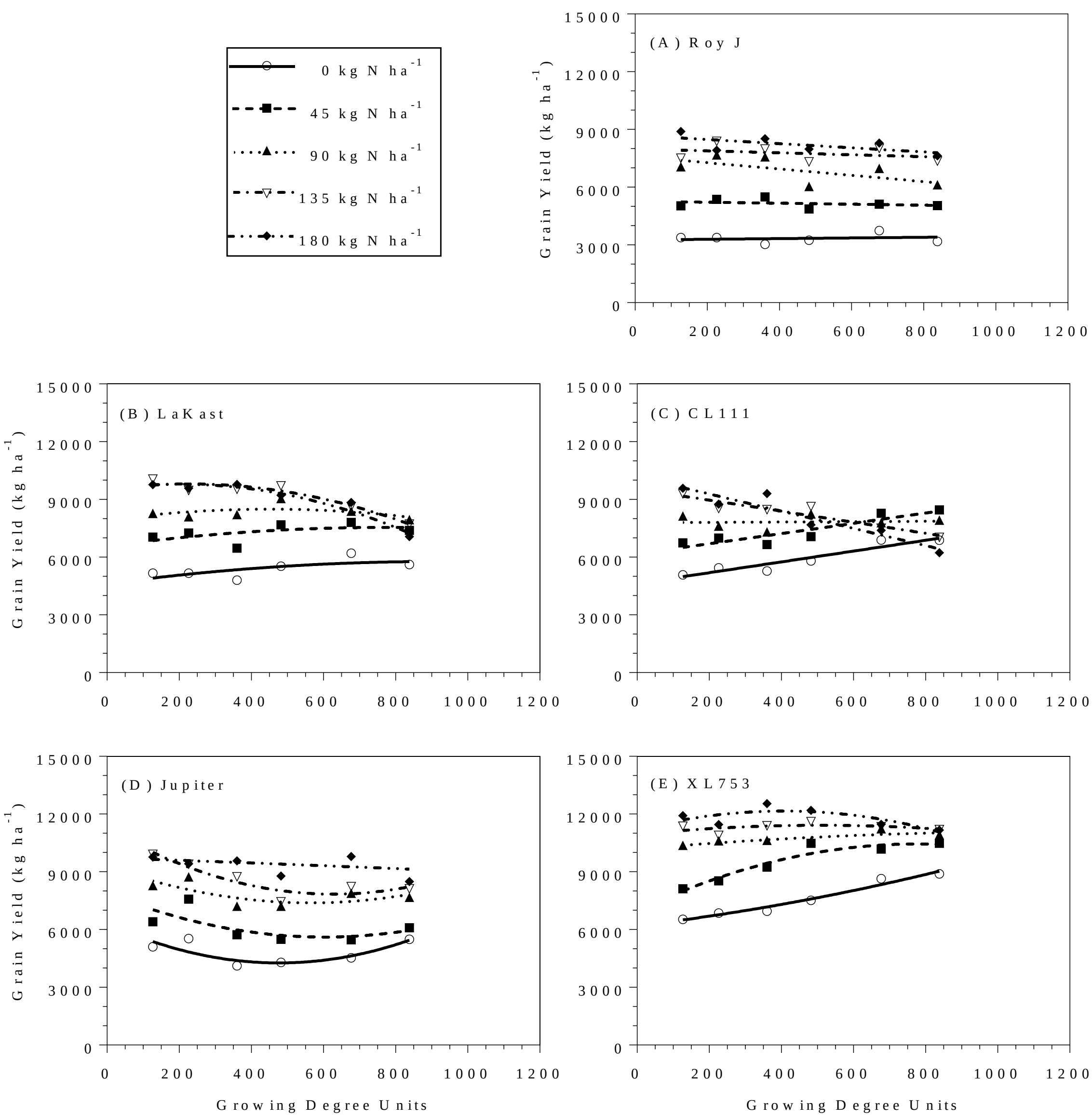
Appendix 2.14. Grain yield for four rice cultivars [(A) Roy J, (B) LaKast, (C) CL111, (D) Jupiter] receiving five different N rates regressed across growing degree units accumulated at the time of fertilization at the Pine Tree Research Station (PTRS-2016). Regression coefficients are listed in Appendix 2.10.



Appendix 2.15. Grain yield for five rice cultivars [(A) Roy J, (B) LaKast, (C) CL111, (D) Jupiter, (E) XL753] receiving five different N rates regressed across growing degree units accumulated at the time of fertilization at the Rice Research and Extension Center (RREC-2015). Regression coefficients are listed in Appendix 2.11.



Appendix 2.16. Grain yield for five rice cultivars [(A) Roy J, (B) LaKast, (C) CL111, (D) Jupiter, (E) XL753] receiving five different N rates regressed across growing degree units accumulated at the time of fertilization at the Rice Research and Extension Center (RREC-2016). Regression coefficients are listed in Appendix 2.11.



Appendix 2.17. Correlation coefficients for cumulative growing degree units accumulated at the time of fertilization, yield, and yield components for Roy J receiving 135 kg N ha^{-1} at the Pine Tree Research Station (PTRS) in 2015a.

Pearson correlation coefficients
Prob > |r| under H0: Rho=0
Number of observations = 24

	Act yld †	Rel yld	GDU	Panicles	Eff tillers	Tillers	Spike	PF spike	Seed wt
Act yld	1.000	1.000	-0.368	0.081	0.280	0.089	-0.158	0.387	0.406
	--	<0.001	0.077	0.705	0.184	0.681	0.461	0.062	0.049
Rel yld	1.000	1.000	-0.368	0.081	0.280	0.089	-0.158	0.387	0.406
	<0.001	--	0.077	0.705	0.184	0.681	0.461	0.062	0.049
GDU	-0.368	-0.368	1.000	-0.385	-0.223	-0.332	0.689	-0.420	-0.854
	0.077	0.077	--	0.063	0.294	0.113	<0.001	0.041	<0.001
Panicles	0.081	0.081	-0.385	1.000	0.447	0.615	-0.356	-0.194	0.296
	0.705	0.705	0.063	--	0.029	0.001	0.088	0.364	0.160
Eff tillers	0.280	0.280	-0.223	0.447	1.000	-0.258	-0.285	0.375	0.281
	0.184	0.184	0.294	0.029	--	0.223	0.178	0.071	0.183
Tillers	0.089	0.089	-0.332	0.615	-0.258	1.000	-0.090	-0.218	0.248
	0.681	0.681	0.113	0.001	0.223	--	0.675	0.305	0.243
Spike	-0.158	-0.158	0.689	-0.356	-0.285	-0.090	1.000	-0.244	-0.706
	0.461	0.461	0.001	0.088	0.178	0.675	--	0.251	0.001
PF spike	0.387	0.387	-0.420	-0.194	0.375	-0.218	-0.244	1.000	0.602
	0.062	0.062	0.041	0.364	0.071	0.305	0.251	--	0.002
Seed wt	0.406	0.406	-0.854	0.296	0.281	0.248	-0.706	0.602	1.000
	0.049	0.049	<0.001	0.160	0.183	0.243	<0.001	0.002	--

† Abbreviations for the correlation analysis represent: Act yld, actual grain yield (kg ha^{-1}); Rel yld, relative grain yield (%); GDU, growing degree units (DD10); Panicles, panicle number (panicles m^{-2}); Eff tillers, effective tillers (% tillers bearing panicles); Tillers, tiller number (tillers plant^{-1}); Spike, total spikelet number (spikelets panicle^{-1}); PF spike, % filled spikelets; Seed wt, seed weight (mg seed^{-1}).

Appendix 2.18. Correlation coefficients for cumulative growing degree units accumulated at the time of fertilization, yield, and yield components for Roy J receiving 135 kg N ha^{-1} at the Pine Tree Research Station (PTRS) in 2016.

Pearson correlation coefficients
Prob > |r| under H0: Rho=0
Number of observations = 28

	Act yld †	Rel yld	GDU	Panicles	Eff tillers	Tillers	Spike	PF spike	Seed wt
Act yld	1.000	1.000	-0.799	0.428	0.760	-0.230	0.399	0.607	0.599
	--	<0.001	<0.001	0.026	<0.001	0.259	0.039	0.001	0.001
Rel yld	1.000	1.000	-0.799	0.428	0.760	-0.230	0.399	0.607	0.599
	<0.001	--	<0.001	0.026	<0.001	0.259	0.039	0.001	0.001
GDU	-0.799	-0.799	1.000	-0.058	-0.768	0.502	-0.576	-0.542	-0.733
	<0.001	<0.001	--	0.771	<0.001	0.008	0.001	0.003	<0.001
Panicles	0.428	0.428	-0.058	1.000	0.392	0.361	-0.059	0.086	0.066
	0.026	0.026	0.771	--	0.039	0.064	0.766	0.665	0.739
Eff tillers	0.760	0.760	-0.768	0.392	1.000	-0.514	0.392	0.517	0.611
	<0.001	<0.001	<0.001	0.039	--	0.006	0.039	0.005	0.001
Tillers	-0.230	-0.230	0.502	0.361	-0.514	1.000	-0.077	-0.448	-0.520
	0.259	0.259	0.008	0.064	0.006	--	0.704	0.019	0.005
Spike	0.399	0.399	-0.576	-0.059	0.392	-0.077	1.000	0.401	0.293
	0.039	0.039	0.001	0.766	0.039	0.704	--	0.035	0.130
PF spike	0.607	0.607	-0.542	0.086	0.517	-0.448	0.401	1.000	0.708
	0.001	0.001	0.003	0.665	0.005	0.019	0.035	--	<0.001
Seed wt	0.599	0.599	-0.733	0.066	0.611	-0.520	0.293	0.708	1.000
	0.001	0.001	<0.001	0.739	0.001	0.005	0.130	<0.001	--

† Abbreviations for the correlation analysis represent: Act yld, actual grain yield (kg ha^{-1}); Rel yld, relative grain yield (%); GDU, growing degree units (DD10); Panicles, panicle number (panicles m^{-2}); Eff tillers, effective tillers (% tillers bearing panicles); Tillers, tiller number (tillers $plant^{-1}$); Spike, total spikelet number (spikelets $panicle^{-1}$); PF spike, % filled spikelets; Seed wt, seed weight (mg $seed^{-1}$).

Appendix 2.19. Correlation coefficients for cumulative growing degree units accumulated at the time of fertilization, yield, and yield components for Roy J receiving 90 kg N ha^{-1} at the Rice Research and Extension Center (RREC) in 2015.

Pearson correlation coefficients
Prob > |r| under H0: Rho=0
Number of observations = 20

	Act yld †	Rel yld	GDU	Panicles	Eff tillers	Tillers	Spike	PF spike	Seed wt
Act yld	1.000	1.000	0.016	-0.091	-0.022	-0.107	-0.053	-0.059	-0.006
	--	<0.001	0.946	0.703	0.925	0.654	0.823	0.804	0.981
Rel yld	1.000	1.000	0.016	-0.091	-0.022	-0.107	-0.053	-0.059	-0.006
	<0.001	--	0.946	0.703	0.925	0.654	0.823	0.804	0.981
GDU	0.016	0.016	1.000	0.210	0.071	0.145	-0.455	0.712	-0.391
	0.946	0.946	--	0.375	0.766	0.543	0.044	0.001	0.088
Panicles	-0.091	-0.091	0.210	1.000	0.616	0.786	-0.199	-0.187	-0.426
	0.703	0.703	0.375	--	0.004	<0.001	0.400	0.431	0.061
Eff tillers	-0.022	-0.022	0.071	0.616	1.000	0.282	0.044	-0.112	-0.156
	0.925	0.925	0.766	0.004	--	0.228	0.855	0.638	0.512
Tillers	-0.107	-0.107	0.145	0.786	0.282	1.000	-0.169	-0.181	-0.515
	0.654	0.654	0.543	<0.001	0.228	--	0.476	0.445	0.020
Spike	-0.053	-0.053	-0.455	-0.199	0.044	-0.169	1.000	-0.509	0.770
	0.823	0.823	0.044	0.400	0.855	0.476	--	0.022	<0.001
PF spike	-0.059	-0.059	0.712	-0.187	-0.112	-0.181	-0.509	1.000	-0.329
	0.804	0.804	0.001	0.431	0.638	0.445	0.022	--	0.156
Seed wt	-0.006	-0.006	-0.391	-0.426	-0.156	-0.515	0.770	-0.329	1.000
	0.981	0.981	0.088	0.061	0.512	0.020	<0.001	0.156	--

† Abbreviations for the correlation analysis represent: Act yld, actual grain yield (kg ha^{-1}); Rel yld, relative grain yield (%); GDU, growing degree units (DD10); Panicles, panicle number (panicles m^{-2}); Eff tillers, effective tillers (% tillers bearing panicles); Tillers, tiller number (tillers plant^{-1}); Spike, total spikelet number (spikelets panicle^{-1}); PF spike, % filled spikelets; Seed wt, seed weight (mg seed^{-1}).

Appendix 2.20. Correlation coefficients for cumulative growing degree units accumulated at the time of fertilization, yield, and yield components for Roy J receiving 135 kg N ha^{-1} at the Rice Research and Extension Center (RREC) in 2016.

Pearson correlation coefficients
Prob > |r| under H0: Rho=0
Number of observations = 24

	Act yld †	Rel yld	GDU	Panicles	Eff tillers	Tillers	Spike	PF spike	Seed wt
Act yld	1.000	1.000	-0.239	0.048	0.196	-0.161	0.385	0.029	-0.315
	--	<0.001	0.261	0.827	0.371	0.464	0.070	0.897	0.143
Rel yld	1.000	1.000	-0.239	0.048	0.196	-0.161	0.385	0.029	-0.315
	<0.001	--	0.261	0.827	0.371	0.464	0.070	0.897	0.143
GDU	-0.239	-0.239	1.000	-0.460	-0.575	-0.044	0.009	0.103	-0.016
	0.261	0.261	--	0.027	0.004	0.843	0.966	0.641	0.943
Panicles	0.048	0.048	-0.460	1.000	0.203	0.687	-0.273	-0.268	-0.046
	0.827	0.827	0.027	--	0.353	<0.001	0.207	0.217	0.836
Eff tillers	0.196	0.196	-0.575	0.203	1.000	-0.394	0.100	-0.039	0.045
	0.371	0.371	0.004	0.353	--	0.063	0.649	0.858	0.839
Tillers	-0.161	-0.161	-0.044	0.687	-0.394	1.000	-0.427	-0.208	-0.121
	0.464	0.464	0.843	<0.001	0.063	--	0.042	0.342	0.584
Spike	0.385	0.385	0.009	-0.273	0.100	-0.427	1.000	0.189	-0.243
	0.070	0.070	0.966	0.207	0.649	0.042	--	0.387	0.264
PF spike	0.029	0.029	0.103	-0.268	-0.039	-0.208	0.189	1.000	-0.415
	0.897	0.897	0.641	0.217	0.858	0.342	0.387	--	0.049
Seed wt	-0.315	-0.315	-0.016	-0.046	0.045	-0.121	-0.243	-0.415	1.000
	0.143	0.143	0.943	0.836	0.839	0.584	0.264	0.049	--

† Abbreviations for the correlation analysis represent: Act yld, actual grain yield (kg ha^{-1}); Rel yld, relative grain yield (%); GDU, growing degree units (DD10); Panicles, panicle number (panicles m^{-2}); Eff tillers, effective tillers (% tillers bearing panicles); Tillers, tiller number (tillers $plant^{-1}$); Spike, total spikelet number (spikelets $panicle^{-1}$); PF spike, % filled spikelets; Seed wt, seed weight (mg $seed^{-1}$).

Chapter 3

Conclusions

Conclusions

The effect of fertilization and flooding time on the development and yield of rice grown in a direct-seeded, delayed flood production system has not been thoroughly examined. The current recommended time to apply preflood urea-N to a direct-seeded, delayed-flood system is when rice reaches the 4- to 5-leaf growth stage (195-310 growing degree units, GDU) with the final recommended time being 16 d (287 GDU) prior to 1.25 cm internode elongation. The overall research goal was to determine whether the current recommendation pertaining to how long preflood-N can be delayed is accurate or needs revision. The specific research objective were to evaluate the effect of preflood-N and flood establishment time and fertilizer-N rate on the 1) grain yield and 50% heading time of multiple rice cultivars that differ in growth duration (e.g., days to maturity) and 2) aboveground-N content, tillering, and yield components (panicle bearing tillers, spikelet number panicle^{-1}, percentage of filled spikelets, seed weight) of a single rice cultivar (Roy J).

The results confirmed that the time at which rice was fertilized and flooded influenced aboveground-N content, maturity, yield components, and grain yield but the response depended upon cultivar, location, or both. As fertilization and flooding were delayed beyond the 5-leaf stage, rice aboveground-N content increased across fertilization and flood timings for three of the four site-years. However, fertilizer nitrogen recovery efficiency remained constant for each fertilization rate across all fertilization and flooding times, suggesting that the increase in total aboveground-N content was due to increased rice uptake of native soil-N since the aboveground-N content for rice receiving no fertilizer-N increased as flooding was delayed.

The delay in preflood-N application time and flooding had a significant effect on the relative delay in 50% heading that depended on N rate and cultivar. In general, the delay in 50%

heading was linear or quadratic, increased as N rate increased and increased as the delay in fertilization and flooding increased. The delay in 50% was 0.3 to 0.7 d heading delay per d^{-1} delay in fertilization and flooding.

Delaying fertilization and flooding until 838 GDU (32 d beyond 5-leaf), the latest fertilization time, had no effect on grain yield of rice grown on a Dewitt silt loam at the Rice Research and Extension Center (RREC). Likewise, the yield components of rice on the Dewitt silt loam showed no consistent effect from fertilization time. In contrast, delaying fertilization beyond 531 GDU on a Calhoun silt loam at the Pine Tree Research Station (PTRS) resulted in significant yield reductions that were negatively correlated with seed weight and percentage filled spikelets. The exact reasons for the difference between the two soils are unknown but may be related to the Dewitt silt loam having a lower N requirement due to native soil-N availability compared to the Calhoun soil. Fertilization and flooding were also not delayed as long on the of the Dewitt silt loam compared to the research performed on the Calhoun soil. Additional research is needed to examine whether clayey soils, which tend to have a greater N requirement than loamy soils respond to fertilization and flooding time similar to the Calhoun soil.

Based on the results of multiple site-years of research on two silt loam soils the current recommendation for the absolute deadline for applying preflood-N fertilizer is still valid and would not result in yield loss if growers delayed preflood-N until approximately 16 d (287 GDU) prior to 1.25 cm internode elongation. For the five cultivars included in this research, the 531 GDU threshold where yield began to decline at the PTRS is 221 to 336 GDU (approximately 13 to 20 d) beyond the current recommended optimal period to apply preflood-N and 96 GDU (about 6 d) beyond the average final recommended time to apply preflood-N. The results actually suggest that the preflood-N could be delayed more than the current recommendation without adversely affecting rice grain yield. The findings may also have implications for the production of rice in non-flooded environments in that rice development is delayed by delays in N-fertilization and flooding and for rice production in systems with limited fertilizer-N sources (e.g., organic). Delayed flooding tended to increase rice aboveground-N content and grain yield when suboptimal N rates were applied.